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Effects of Hydrological Connectivity on the Benthos of a Large River (Lower Mississippi River, USA)

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EFFECTS OF HYDROLOGICAL CONNECTIVITY ON THE BENTHOS OF A LARGE RIVER (LOWER MISSISSIPPI RIVER, USA)

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ABSTRACT

The effects of hydrological connectivity between the Mississippi River main channel and adjacent secondary channel and floodplain habitats on macroinvertebrate community structure, water chemistry, and sediment makeup and chemistry are analyzed. In river-floodplain systems, connectivity between the main channel and the surrounding floodplain is critical in maintaining ecosystem processes. Floodplains comprise a variety of aquatic habitat types, including frequently connected secondary channels and oxbows, as well as rarely connected backwater lakes and pools. Herein, the effects of connectivity on riverine and floodplain biota, as well as the impacts of connectivity on the physiochemical makeup of both the water and sediments in secondary channels are examined. Between June 2014 and August 2016, twenty-six sites spanning a gradient of hydrological connectivity to the main channel of the Mississippi River were sampled. First, macroinvertebrate community structure across the floodplain was analyzed, and a strong association between community types present and frequency of connection was found. Next, the effects of hydrologic connectivity on macroinvertebrate communities in secondary channels was investigated. These results indicate the loss of connectivity through seasonal disconnection of secondary channels from the main channel causes a shift from a lotic to lentic environment, and then a legacy effect, a macroinvertebrate

void, when connectivity is restored. Finally, connectivity also affects the physiochemical dynamics of water and sediments within secondary channels, transforming disconnected channels into backwater habitats, characterized by warmer temperatures, lower dissolved oxygen concentrations, and sediments rich in organic matter. Colonization of these new pools and slackwater habitats by lentic macroinvertebrate communities occurs, but both the community changes and changes in the nutrient load and sediment makeup are temporary, only persisting until reconnection to the river channel occurs.

DEDICATION

This work is dedicated to my family. Without your continued support, this project would not have been possible. I express my deepest gratitude for sharing in my burdens and successes, for reducing my workload whenever possible, and for making yourselves available when needed or asked. Through me, may my dearest Eleanor see that she can accomplish what she works hard for, and through you, may she see that such achievements are rarely, if ever, done by oneself.

LIST OF ABBREVIATIONS AND SYMBOLS

ANOVA – Analysis of Variance

AWI – America's Watershed Initiative; A multi-agency working group focused on determining, monitoring, and improving the health of the Mississippi River Watershed.

CPUE – Catch Per Unit Effort: An indirect comparison of sample abundance in a single effort between different gear types.

ERDC – US Army Engineer Research and Development Center, Vicksburg, MS

GIS – Geographic Information System

Km – Kilometer

LiDAR – Light Detection and Ranging

LMR – Lower Mississippi River: The free-flowing Mississippi River from its confluence with the Ohio River at Cairo, IL, to its mouth at the Gulf of Mexico.

LMRCC – Lower Mississippi River Conservation Committee

nMDS – Non-metric Multidimensional Scaling

mMDS – Metric Multidimensional Scaling

PCA – Principle Components Analysis

PERMANOVA – Permutational Multivariate Analysis of Variance

Rkm – River kilometer

RM – River Mile: Unit of measurement used in USACE Navigation Charts, beginning at RM 0 at the Head of Passes near Venice, LA, to RM 953.5 at the confluence with the Ohio River at Cairo, IL.

SIMPER – Similarity Percentages Procedure

USACE – United States Army Corps of Engineers

USFWS – United States Fish and Wildlife Service

WSE – Water Surface Elevation (ft)

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CHAPTER I: INTRODUCTION

The role of habitat connectivity in ecosystem health and function is at the forefront of ecological research, and considers fragmented habitats of all types. Individual ecosystems are not closed systems, so input from other ecosystems is required to maintain natural ecosystem processes such as trophic interactions, nutrient processing, and movement of individuals. In aquatic systems, connectivity is often viewed in the context of hydrological connectivity, or the multidirectional movement of water across space (Amoros and Bornette 2002; Amoros et al. 1987; Ward 1989; Ward and Stanford 1995). In this context, connectivity can be studied across aquatic habitat types, from habitats that are rarely or never connected to each other, to those that are almost always or fully connected. A river-floodplain ecosystem provides an excellent research area for the study of connectivity. The geophysical processes that formed river systems over evolutionary time, carved out habitats varying in their connectivity to each other. Often, river-floodplain connectivity is considered as connection of water bodies to the river itself, allowing for the determination of connection thresholds, and establishment of a connectivity gradient for examination (Ward and Stanford 1995).

Worldwide, all rivers and streams have been modified by humans to control flow, prevent flooding, provide energy, and transport goods (Arthington 2012; Benke and Cushing 2005). These anthropogenic modifications have drastically altered the form and function of natural flowing waterways. Changes to connectivity thresholds, frequencies, and durations are among these modifications, have occurred as a result of human modification of river systems. A good example is the Lower Mississippi River System,

which has been drastically altered from its natural state (Baker et al. 1991; Fremling et al. 1989).

For thousands of years, in its natural state, the Mississippi River meandered freely, flooded regularly, was surrounded by lush bottomland hardwood forests, permanent and seasonal wetlands, and peppered with prairies (Benke and Cushing 2005). Over the course of a century and a half, however, human modification has altered dramatically the morphology, flow regime, chemistry, and ecological function of the Mississippi River. These modifications include deforestation of hardwood forests for agricultural land uses, construction of flood control structures such as levees, shortening the river by cutting off river bends, armoring the river banks with concrete mattresses (revetments), and altering the water chemistry by inputs of chemical fertilizers, pesticides, herbicides, and human wastes (sewage and garbage) (Arthington 2012; Baker et al. 1991; Divers et al. 2009).

Each of these modifications has its own effect(s) on the physical habitat and the ecology of the system. Many of the ecological effects of river engineering are poorly known, because modification predated the modern environmental movement and large rivers are notoriously difficult to sample (Benke and Cushing 2005). However, the presence or absence of ecological indicators can help scientists understand the biological and physical responses to habitat alterations, as well as direct future restoration efforts (Lenat 1988; Metcalfe 1989; Niemi and McDonald 2004). The intent of this study is three-fold, but is structured by the same overarching question, “What are the effects of a gradient of hydrological connectivity on (1) macroinvertebrate community structure

across the river-floodplain, (2) the macroinvertebrate communities in naturally occurring secondary channels, (3) physiochemical properties of water and sediment?"

To answer these questions, a 156-rkm reach (Figure 1.1) of the Lower Mississippi River (chosen for its proximity to the University of Mississippi and accessibility), and its floodplain was sampled multiple times over three years (2014-2016). Habitat types sampled ranged from the permanently flowing river channel to secondary channels, oxbow lakes, backwater chutes, and floodplain lakes. Collections included macroinvertebrates, sediments, and water.

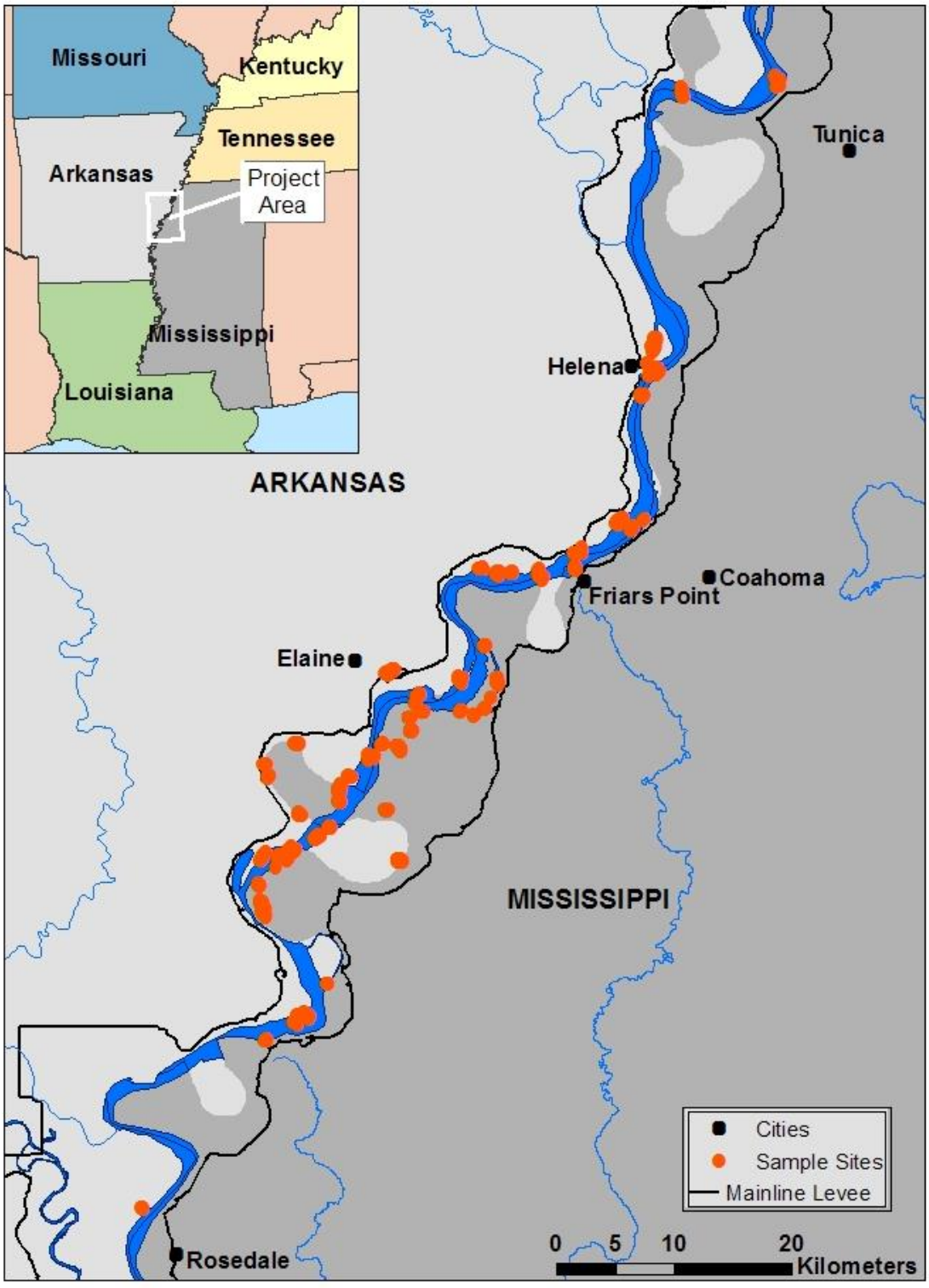

Figure 1.1. Project study reach (RM 591-688).

CHAPTER II:

RELIABLE AND EFFECTIVE SAMPLING GEAR TYPE FOR LARGE RIVER MACROINVERTEBRATES

ABSTRACT

Benthic macroinvertebrates are touted as excellent indicators of ecological condition, water quality, and environmental history, and are used to assess biotic integrity of fluvial systems worldwide. These organisms are sampled most frequently in wadeable streams, less commonly in larger water bodies. Large river macroinvertebrates are notoriously difficult to sample, particularly those residing on and within benthic substrates. Following repeated difficulties in acquiring benthic macroinvertebrate samples in the Lower Mississippi River, USA, using commercially available samplers, we sought to find a gear type that samples reliably and effectively over all riverine substrates and flow conditions. We developed and tested a benthic sled and present its sampling efficacy. One sampling effort (72 samples) in June 2014 yielded a total of 54 unique taxa (>2400 individuals). Considering its reliability and effectiveness, we advocate the use of this gear type over commercially available grab-type samplers for sampling substrates in large rivers, especially when describing and monitoring macroinvertebrate communities and conducting bioassessments.

Introduction

Aquatic macroinvertebrates are useful in the analysis of habitat quality, biotic response, water quality, and biological diversity. Because of the life history complexities and occupancy of a wide variety of functional guilds, macroinvertebrates are ideal indicator organisms for many environmental assessments (Merritt et al. 2008). In lotic

systems, these analyses are largely limited to habitats that are easily accessible, such as wadeable streams. In small to mid-sized streams and rivers, bank and benthic habitats can be sampled with a suite of sampling equipment (qualitative and quantitative) such as kick nets, kick screens, Surber samplers, air-lift samplers, grabs, and corers (Merritt et al. 2008). There has been increasing effort and interest in sampling macroinvertebrates in large, non-wadeable river systems, but sampling can be problematic logistically, especially when describing benthic-oriented communities inhabiting large spatial areas (Angradi 2006; Bartsch et al. 1998, Blocksom and Flotemersch 2005; Merritt et al. 2005; Flotemersch et al. 2006a, b). Bioassessment protocols for non-wadeable streams prescribe the use of kick nets along channel borders, and snag nets where large woody debris are present (Angradi 2006; Blocksom and Flotemersch 2005). Due to landscape level land use and river modification, many large rivers, however have lost much of their former structural complexity, and habitats such as snags, log jams, and other large woody debris are no longer common, if present at all (Allan 2004; Baker et al. 1991). For example, North American large rivers such as the Lower Mississippi River, Lower Missouri River, and Ohio River, have been modified extensively (Baker et al. 1991; Benke and Cushing 2005; Killgore et al. 2014), eliminating most snag habitat and making banks unsafe for sampling using traditional hand-held nets. Further, water depths and velocities vary with river stage, complicating repeated sampling efforts over multiple seasons, and making some gear types unreliable and impractical.

For time and cost savings, as well as safety, there is a need for a reliable gear type for sampling all benthic habitats at all river stages (Beckett et al. 1983b). Historically, drag or dredge samplers, which are pulled across the benthos, have been used for benthic

sediment sampling and community assessments in marine habitats (e.g., Kaiser and Brenke 2016; MacIntyre 1964; Snell 1998), with limited use in freshwater habitats (Bournaud et al. 1998; Elliot and Drake 1981; Nielson and Johnson 1983). Studies comparing the effectiveness of grab samplers versus dredge samplers in riverine habitats are rare, but those available provide data supporting the use of dredge samplers over grab samplers in lotic systems (Elliot and Drake 1981; Fast 1968). In this study, we utilized a modified skimmer dredge (*sensu* Miller et al. 1989), hereafter "benthic sled", and tested its utility sampling the benthos of a large, fast-flowing river. To provide context, we compare sampling results (catch per unit effort - CPUE) to that of a previous sampling effort using a common benthic sediment sampler, the Ponar grab.

Materials and Procedures

Materials

A skimmer dredge originally designed for sampling freshwater mussels (see Miller et al. 1989) was modified for sampling macroinvertebrates in the Lower Mississippi River, USA. The benthic sled opening measures 47 cm x 20 cm and has an adjustable scraper blade that helps control the sediment depth sampled and deflect organisms into the collection net (Figure 2.1). Skids measuring 116 cm in length and 7.5 cm in width aid in correct positioning of the sled on the substrate. Tines measuring 2.5 cm long and 0.6 cm in diameter were welded onto the scraper blade to help dislodge organisms in the substrate. The steel frame of the skimmer dredge was outfitted with a 500-µm mesh inner net, a 2-cm mesh outer net, and a 2-cm mesh skirt along the bottom of the net for protection of the fine mesh. The fine mesh netting was reinforced with

canvas along seams and was tied off at the rear of the net with nylon strings, one attached to the inner net and one attached to the outer net.

Procedures

Within a 95 km reach of the Lower Mississippi River (Figure 2.2), nine secondary channels and three main channel sites were sampled during 11-12 June 2014 using a benthic sled. Samples were taken on the rising limb of the hydrograph during a high river stage, typical of the spring pulse (Table 2.1). Six replicate samples were taken at each location, according to a stratified random sampling design, as part of a larger study to capture community dynamics in response to altered hydrologic connectivity. After reaching the sampling location, starting GPS coordinates were recorded and the gear was deployed from the boat, pulled approximately 50 m, and retrieved using a windlass mounted to a boom on the port side. Although sampling distance was measured, the collection net once full likely stops collecting sediment, therefore sample volume was standardized by taking an 8 L subsample of sediment. Sand samples were elutriated using a "stir and pour" technique (e.g., Harrison et al. 2017; Lenat 1988; Soluk 1985) to suspend organic matter, with a minimum of 5 washes per sample, or until water was clear and there were no remaining invertebrates observed. Each wash was poured through a 500-µm sieve. For samples with particle sizes <500-µm (i.e., mud, clay), the entire 8 L subsample was poured through a 500-µm mesh sieve and washed through using a water hose connected to the boat's bilge pump. Sieved material was placed in plastic storage bags preserved with 80% EtOH and returned to the laboratory for sorting and identification. Using an Olympus SZX16 stereo microscope, specimens were sorted by

morphotype, counted, and identified to the lowest taxonomic category possible using the following taxonomic keys: insects (Epler 2001; Merritt et al. 2008; Morse et al. 2017), non-insects (Pennak 1953; Thorp and Covich 1991). Chironomidae specimens were cleared in lactic acid, dehydrated in a series of increasing ethanol concentrations (80%, 90%, 100%) for 10 minutes each, placed in clove oil for 24 hours, and mounted on glass slides using Canada balsam. Slide mounted specimens were then identified using an Olympus BX43 compound microscope. Oligochaetes were not identified to lower taxonomic levels due to poor body condition following processing.

To evaluate CPUE, sled collections were compared to samples taken at the same sites one month prior, during similar river conditions (Table 2.1) using a Ponar grab sampler (*sensu* Powers and Robertson 1967). Because number of organisms per collection varied greatly between the two gears, rarefaction curves and asymptotic estimators of taxa richness were computed on each reference set of abundance data using EstimateS v. 9 software (Colwell 2013). Extrapolation curves and 95% confidence intervals based on unconditional variance estimators were calculated following the methods of Colwell et al. (2012). Community composition by gear and substrate type was examined qualitatively using taxonomic presence/absence per sample depicted in shade plots created using PRIMER v. 7 software (PRIMER-E Ltd, Plymouth, UK).

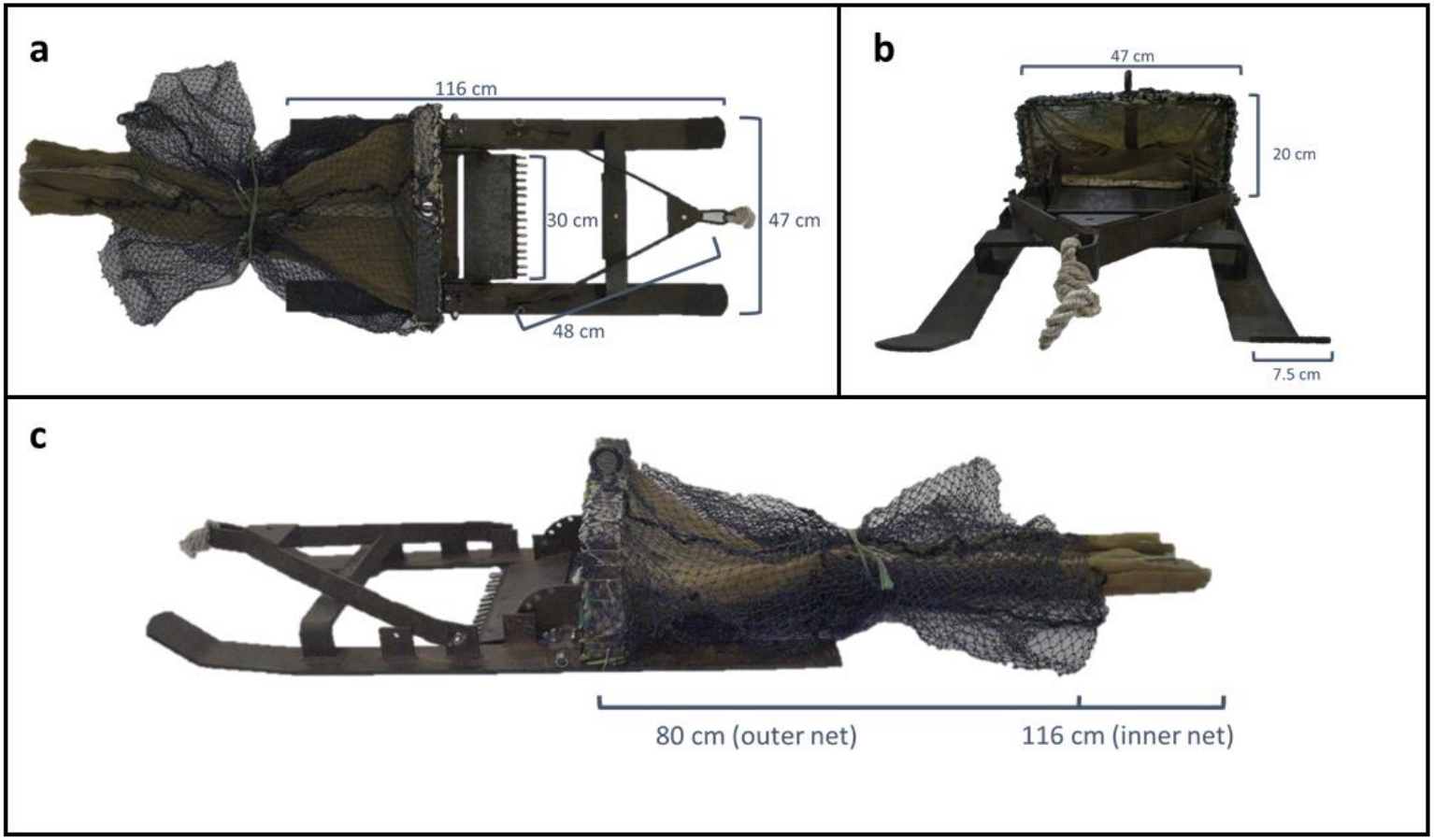

Figure 2.1. Benthic sled dimensions. Dorsal aspect (a), anterior aspect (b), lateral aspect (c).

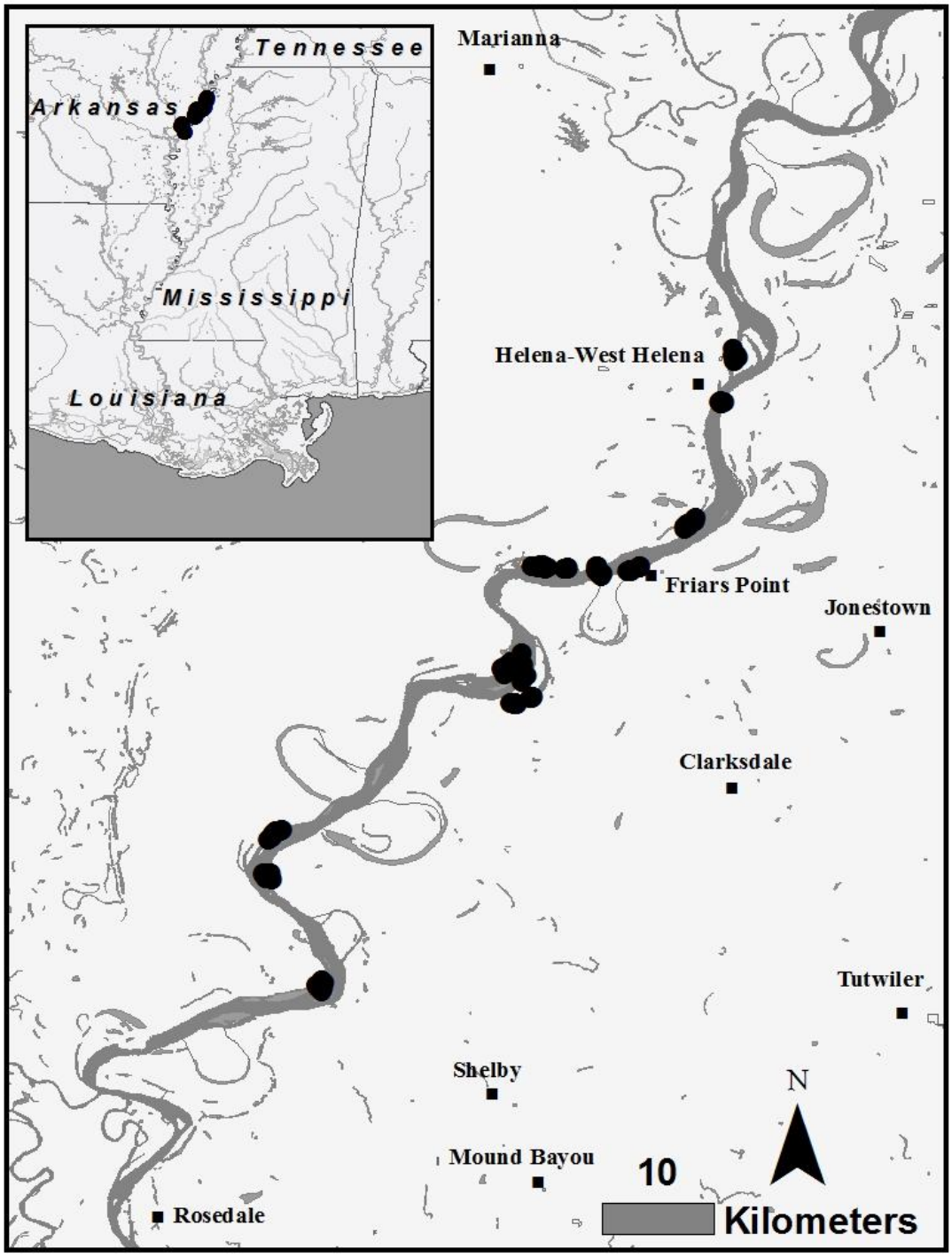

Figure 2.2. Project study reach/sites (black dots). Lower Mississippi River (RM 610 – 668).

Table 2.1. Surface water velocities, depths, and river stage at sample reach. River stage at Helena, AR gage (www.rivergages.com).

Date	Sampling Gear	Average Water Velocity (m/s)	SD	Average Sampling Depth (m)	SD	River Stage (m)
7-8 May 2014	Ponar grab	1.16	0.33	5.56	7.65	9.24
11-12 June 2014	Benthic sled	1.37	0.83	5.44	11.81	7.28

Assessment and Discussion

The benthic sled was very reliable at obtaining a full sample upon first deployment (98.6%) across all sampling depths (see Table 2.1). On average, richness was 4.49 taxa per sample (SD = 3.60) and ranged 0-18. Abundance (density per sample volume) was 34.42 individuals per sample (SD = 111.96) and ranged 0-917. Much of this variation is related to substrate type, habitat quality, and macroinvertebrate patchiness within the Mississippi River, which is largely composed of sand and typically has lower biomass than other substrates (Harrison et al. 2017; Soluk 1985). A post hoc comparison with previously collected samples from the same locations during similar river conditions (Table 2.1; 2.2) using a Ponar grab, illustrated stark differences in gear efficacy and reliability. First, the Ponar grab failed to collect any sediment >25% of the time resulting in multiple redeployments at a single station. This is both time consuming and labor

intensive, and can be dangerous when working in the heavily trafficked navigation channel. The Ponar grab also failed to capture the diversity of organisms present in the Mississippi River (Figure 2.3). Average richness was 0.54 taxa per sample (SD = 0.72) and ranged 0-2. Average abundance was 0.64 individuals per sample (SD = 0.95) and ranged 0-5. A wider variety of benthic macroinvertebrates were collected with the benthic sled for all sampled substrates (Figure 2.3). Individual-based and sample-based interpolation (rarefaction) and extrapolation curves for benthic sled and Ponar grab abundance data are shown in Figure 2.4. Because of the large discrepancy in numbers of individuals collected with the Ponar and the benthic sled, comparison of the individual-based rarefaction curves (Figure 2.4a) is difficult. Sampling effort between the two gears, however, was similar (Ponar n=62; sled n=72) and the sample-based rarefaction curves (Figure 2.4b) demonstrate the advantage of the sled over the Ponar in characterizing the benthic macroinvertebrate assemblage. Non-overlap of 95% confidence intervals constructed from unconditional variance estimators is a conservative criterion of statistical difference (Colwell et al. 2012).

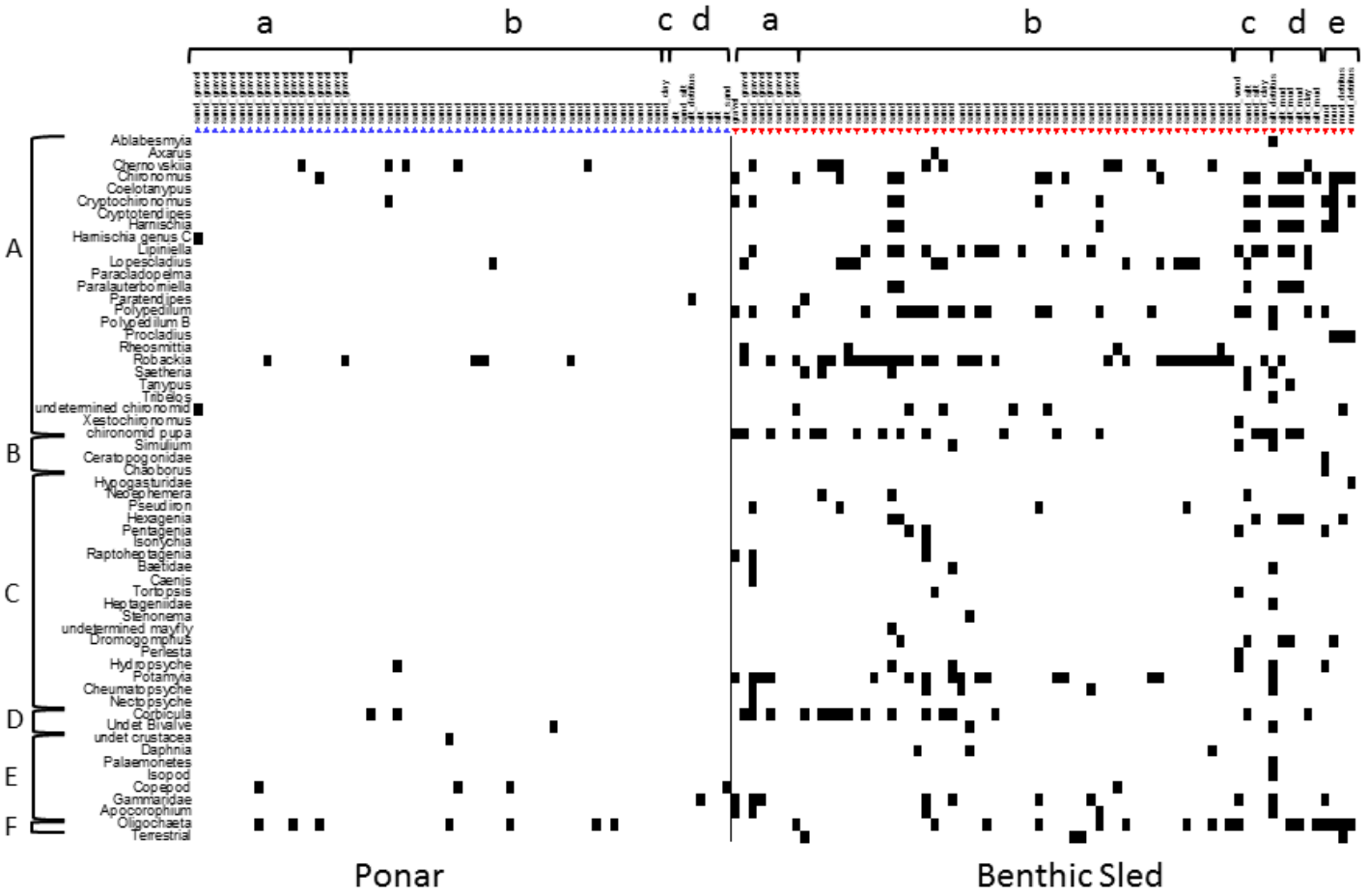

Figure 2.3. Taxonomic presence/absence by gear type and substrate type. Black squares represent presence of taxa. Substrates (upper horizontal axis): a – gravel, gravel mixes; b – sand; c – sand mixes; d – silt, silt mixes; e – mud, mud mixes. Taxa (vertical axis): A – Chironomidae (Insecta: Diptera); B – other Diptera (Insecta); C – other Insecta (Collembola, Ephemeroptera, Odonata, Plecoptera, Trichoptera); D – Bivalvia; E – Crustacea; F – Oligochaeta, terrestrial taxa.

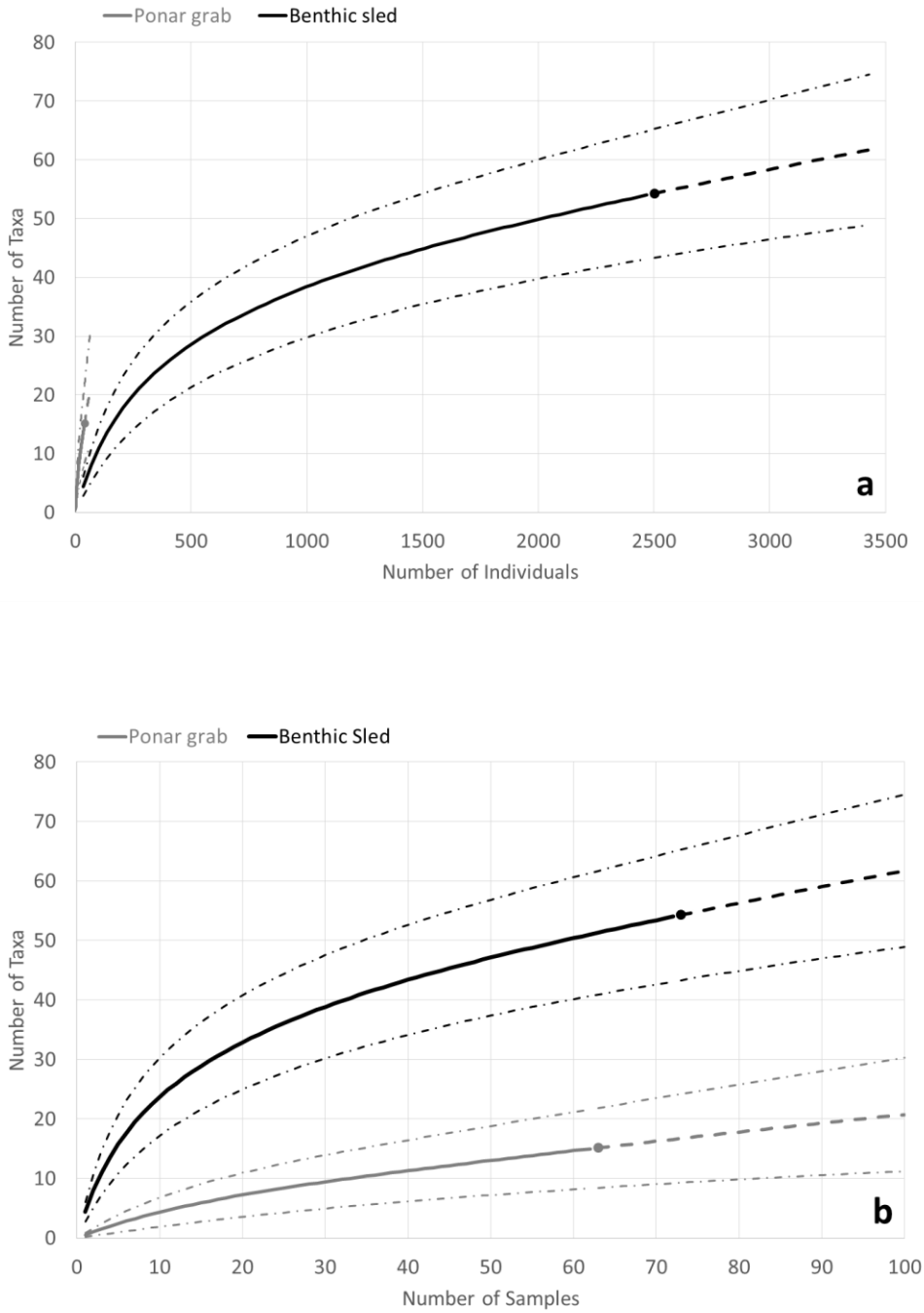

Figure 2.4. Individual-based (a) and sample-based (b) interpolation (heavy solid lines) and extrapolation (heavy dashed lines) curves with 95% unconditional confidence intervals (thin dashed lines) for Ponar grab **(gray)** and benthic sled **(black)** abundance data.

While it is impossible to directly compare abundances (per area) sampled by each gear type, there is a notable difference in CPUE of the two gears in similar sampling conditions. However, both gear types require the same amount of physical and logistical effort. Both are too heavy to be pulled up manually (benthic sled empty = 23.5 kg; Ponar empty = 23 kg), and require a windlass or winch to be retrieved; samples are processed in the same manner. During our sampling efforts of the main channel and secondary channels in the Mississippi River, the Ponar grab was unstable in deeper water with high current, causing the grab to possibly hit the river bottom at an angle, resulting in the jaws closing without obtaining a full sample. Additionally, because most of the substrates composing the Lower Mississippi River and many other large rivers are coarse (i.e., sand, gravel), the jaws do not always fully close, which could allow macroinvertebrates to escape through the bottom while the Ponar grab is being retrieved. Although the Ponar grab has an 8.2 L sample capacity, our average sampling volume was 3.06 L (SD = 1.31). In contrast, the sled is allowed to rest on the substrate before it is pulled along the benthos, which facilitates proper positioning and ample sediment collection in all substrate types, which can then be volumetrically subsampled to a desired amount (e.g., 8 L in our case). Also, because the collection net is tied off at the rear, macroinvertebrates cannot escape during retrieval of the benthic sled.

When designing experiments, the gear type best suited for answering the question at hand should be chosen. When studying benthic community dynamics (e.g., taxonomic composition, structure, response), monitoring populations, and/or conducting bioassessments within large rivers, multiple gear types may be necessary to capture the diversity of these systems. For inclusion of substrate dwelling benthic invertebrates in

community assessments, which represents the majority of available habitat in large rivers, we advocate the use of the benthic sled. It samples reliably across riverine substrates (gravel, sand, silt, mud, and compressed clay) at all depths and velocities, and is more effective than the Ponar grab at capturing macroinvertebrate diversity across similarly sampled habitats.

While grab samplers are ideal for addressing questions regarding biomass and spatial abundance, the benthic sled would not be the appropriate gear type to address those questions. In large rivers, such as the Mississippi, the Ponar grab is ineffective and unreliable and a larger grab, such as the Shipek grab would be more favorable, and has been used with success in this system (Table 2.2), except for in soft substrates, where the force of the sampler hitting the substrate has been shown to displace sediments and organisms (Beckett et al. 1983b; Bingham et al. 1982; Wells and Demas 1979; Wright 1982). The Shipek grab, however, is problematic logistically, because it requires a powerful boom and winch due to its weight (60 kg) and requires a separate cocking wrench to prepare the grab for sampling. The Shipek grab has a reduced sampling volume (3 L) compared to the Ponar grab, likely reducing its CPUE and increasing the number of samples necessary to capture community dynamics (Bartsch et al. 1998). This grab is also quite expensive and may be cost prohibitive for some government agencies and universities seeking to monitor substrate oriented macroinvertebrates. Another widely popular gear type for substrate sampling, air lift samplers, is successfully used in large, stone-bedded European rivers (Drake and Elliott 1982; Jones and Davy-Bowker 2014), but to our knowledge has not been used in the Mississippi River. More research is

needed to test their efficacy in this and other high discharge systems with variable substrata.

Table 2.2. Average numbers of taxa and individuals collected in LMR secondary channels (sites) and number of taxa per sample collected with Ponar grab, benthic sled, and Shipek grab averaged by site (*Baker et al. 1987).

	Average No. Taxa Collected Per Site	**Average No. Individuals Collected per Site**	**No. Sites**	**No. Samples taken per site**	**Total No. Taxa/No. Samples per site**	**Total No. Individuals/ No. Samples per site**	**Date Sampled**
Ponar grab	2.9	3.9	10	6	0.48	0.65	May 2014
Benthic Sled	16.8	260.2	10	6	2.8	43.37	June 2014
Shipek grab*	16.8	359	5	24	0.7	14.958	July 1984

In conclusion, the benthic sled is favorable for sampling substrate-dwelling macroinvertebrates in non-wadeable rivers for three primary reasons: (1) it samples reliably across riverine substrates, including gravel, sand, silt, mud, and compressed clay (2) it effectively samples in a variety of flow conditions, including high current velocities (3) it captures a larger diversity of macroinvertebrates than grab samplers and more accurately characterizes the benthic macroinvertebrate assemblage. Sampling large rivers can be costly and dangerous, exacerbating the need for both reliable and effective gear. In heterogeneous systems, a combination of gear types must be used to fully characterize and monitor faunal distributions and patterns in large rivers (Kaiser and Brenke 2016). Given its relative ease of use, reliability, and efficacy, the benthic sled would be a beneficial addition to bioassessment and biomonitoring sampling protocols, as well as macroinvertebrate community investigations in large rivers worldwide.

Acknowledgements

The benthic sled was conceptualized over lunch at ERDC in Vicksburg, MS, by Dr. Todd Slack, Bradley Lewis, Jay Collins, and me, after disheartening efforts to adequately sample the Lower Mississippi River. My grandmother, Elizabeth Coleman, assisted in the design, and fabricated nets of exceptional quality and durability. In fact, to this date, the original net is intact and has been used to sample LMR substrates many times, from Memphis, TN, to the Head of Passes near the Mississippi Sound below New Orleans, LA.

CHAPTER III:

BENTHIC MACROINVERTEBRATE COMMUNITIES ALONG A GRADIENT OF HYDROLOGICAL CONNECTIVITY WITHIN THE MISSISSIPPI RIVER AND ITS FLOODPLAIN

ABSTRACT

Historically, large floodplain rivers were structurally complex and hydrologically dynamic, and possessed a broad range of habitats from lotic to lentic to predominantly terrestrial. While all large rivers have been simplified to some degree by engineering, along many such systems there remain long reaches of reasonably natural patterns of habitat diversity and spatial distribution. River habitats, from the main channel to the uppermost region of the floodplain, are created and linked to each other by flows of water. For understanding the ecological patterns and processes of such systems, an important question is: What are the relationships of hydrology, habitat structure, and community assemblage of large river-floodplain systems? This question was addressed for a section of the free-flowing Lower Mississippi River floodplain in which natural habitats remain intact, including a variety of water body types embedded in large swaths of bottomland forest. Twelve water bodies spanning a gradient of hydrological connectivity were sampled for benthic macroinvertebrates in the fall, winter, spring, and summer over a two year period. Invertebrate communities variable in taxonomic makeup and richness were found across connectivity types and connection frequencies, indicating a strong relationship between increased environmental stability and community permanence. Water bodies with extended periods of connection or disconnection were found to host a wider variety of macroinvertebrate taxa, while water bodies with intermediate connectivity hosted a more limited suite of taxa. Results from this study

indicate the need for conservation of habitats varying in connection frequency, in order to increase and maintain the highest levels of macroinvertebrate diversity.

Introduction

The influence of connectivity on ecosystem function is evident across a variety of terrestrial and aquatic ecosystems (Cloern 2007; Fahrig and Merriam 1985; Merriam 1984; Taylor et al. 1993). Connectivity research has expanded into freshwater systems and studies have addressed the role of hydrological connectivity on ecosystem processes, movement of individuals, and distribution of populations (Amoros and Bornette 2002; Pongruktham and Ochs 2015; Paillex et al. 2009; Pringle 2003; Tockner et al. 1999; Ward and Stanford 1995). In large river-floodplain ecosystems, such as the Lower Mississippi River (LMR, *sensu* Baker et al. 1991), connectivity of the main stem river to its adjoining floodplain and water bodies varies in degree with the rise and fall of the river. Many river-floodplain species depend on seasonal connectivity or inundation for various life history processes including feeding and reproduction (Galat and Zweimüller 2001; Junk et al. 1989; Sparks et al. 1998). Riverine fish species, for instance, depend on inundation of backwater lakes and forest during high spring flows to access spawning habitats (Baker et al. 1991; Fremling et al. 1989; Junk et al. 1989). Inundation of floodplain habitats also benefits pelagic feeding planktivores and invertivores because fine sediment precipitates out in slack water habitats, increasing light availability for phytoplankton photosynthesis, thereby nourishing invertebrate micro- and macrofauna and providing lentic habitat for rheophobic creatures (Cloern 2007; Pongruktham and Ochs 2015).

While fish are mobile and can readily move in and out of available habitat, aquatic macroinvertebrates are relatively immobile and rely on habitat stability during some life stages (Harvey 1986; Power et al. 1988). For example, immature aquatic insects are dependent on their terrestrial parents to place them into proper habitat during oviposition (Binckley and Resetarits 2007; Ladle and Ladle 1992; Power et al. 1988; Spencer et al. 2002; Statzner et al. 1997). Other movement is limited to self-propulsion via swimming or walking, or in flowing water, drift (Ladle and Ladle 1992; Mackay 1992; Power et al. 1988). In habitats where intermittent hydrologic connectivity causes variable flow regimes, immobility can be problematic for macroinvertebrates specialized for either lotic or lentic conditions, but not both. In some systems, such as ephemeral streams, macroinvertebrates have adapted to seasonal decline or loss of flow (Fisher et al. 1982; Gray 1981; Power et al. 1988), but most aquatic macroinvertebrates rely on habitat stability to complete development, and more stable systems maintain greater biodiversity than frequently disturbed systems (Death and Winterbourn 1995). Due to the need for habitat stability to complete life cycles, it is possible that macroinvertebrate community distributions are not predictable using the intermediate disturbance hypothesis, which states that increased diversity is found in habitats that are frequently, or intermediately disturbed, as compared to highly disturbed or relatively stable habitats (Connell 1978; Townsend et al. 1997).

In river-floodplain ecosystems, inundation varies seasonally and annually and in some habitats could be considered a disturbance, which raises the following questions: How does hydrological connectivity influence benthic community structure? Specifically, does connectivity affect the evenness of river-floodplain macroinvertebrate communities?

Does benthic macroinvertebrate community structure reflect a connectivity gradient? To address these questions, we compared the structure of benthic macroinvertebrate communities at sites along the LMR across a gradient in degree of connectivity to the main stem river channel.

Methods

Site Selection and Connectivity

Twelve sites within the Lower Mississippi River and its floodplain were sampled over the course of two years, October 2014 – August 2016 (Table 3.1; Figure 3.1). Sites were selected using historic aerial photography at varying river stages and topographic maps to represent four connectivity classifications: eupotamal, parapotamal, plesiopotamal, and paleopotamal according to Ward and Stanford (1995), which range from highly connected to rarely connected, respectively (Figures 3.1, 3.2).

Table 3.1. Sites sampled during study period (fall 2014- summer 2016), number of samples collected, and gear(s) used (S=benthic sled; P=Petite Ponar; E=Ekman grab).

Connectivity	Site	Fall 2014	Winter 2015	Spring 2015	Summer 2015	Fall 2015	Summer 2016	Number of Samples	Gear(s)
Eupotamal	Island 63 Secondary Channel			x	x		x	27	S
Eupotamal	Island 64 Secondary Channel			x	x		x	27	S
Eupotamal	Sunflower Dikes Channel			x	x		x	15	S
Parapotamal	Desoto Lake	x	x	x	x		x	30	P
Parapotamal	Glory Hole	x	x		x		x	12	P
Parapotamal	Mellwood Lake		x	x		x	x	33	P
Plesiopotamal	Graveyard Bluehole	x	x	x	x		x	15	P
Plesiopotamal	Jim Samples Lake	x	x	x	x		x	15	P
Plesiopotamal	McWilliams Lake	x	x	x	x		x	15	P, E
Plesiopotamal	Old River Chute	x	x	x	x		x	15	P, E
Paleopotamal	Borrow Pit A		x	x		x	x	12	P
Paleopotamal	Borrow Pit B		x	x		x	x	12	P

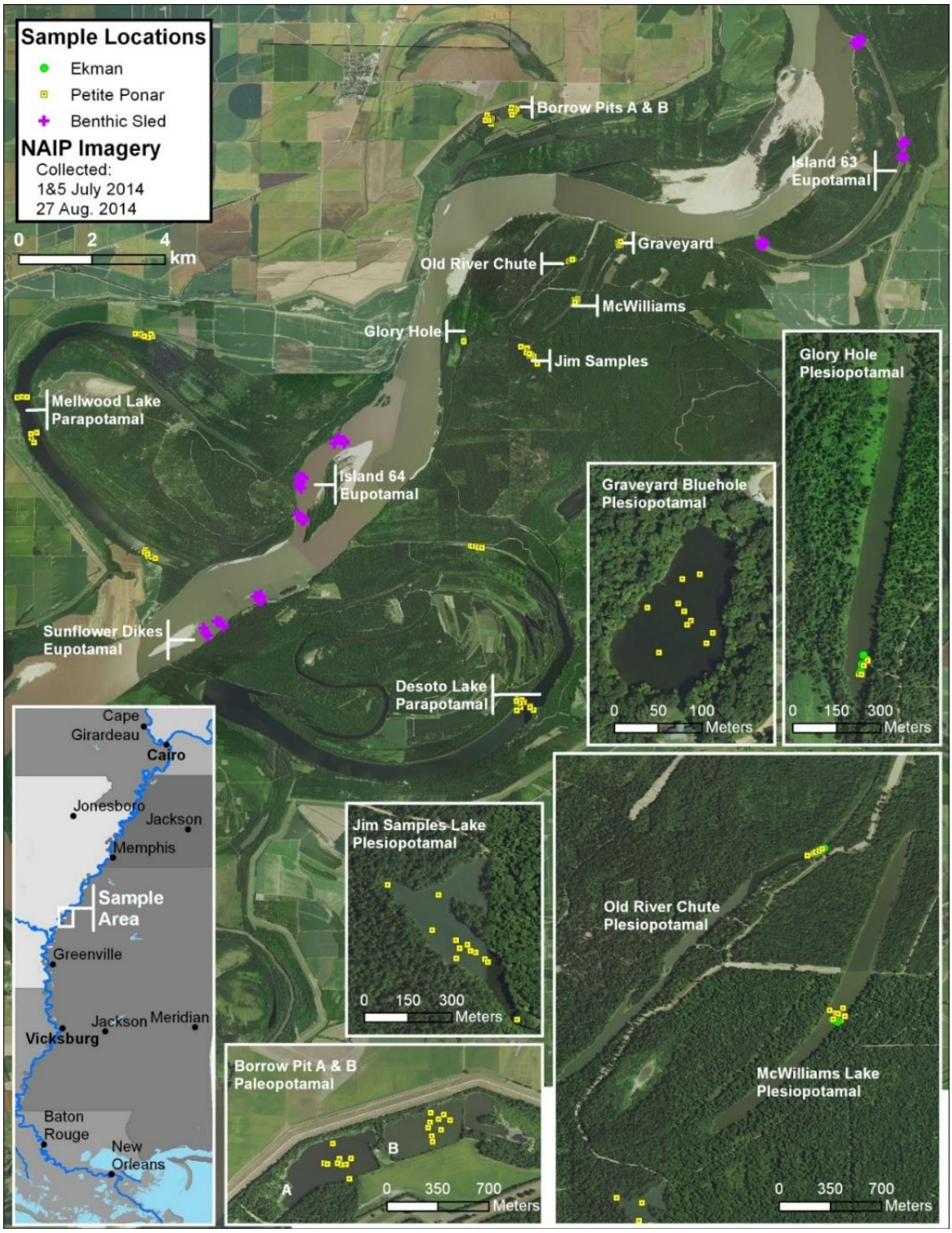

Figure 3.1. Water bodies and their connectivity type sampled October 2014 to August 2016 using petite Ponar grab, Ekman grab, or benthic sled.

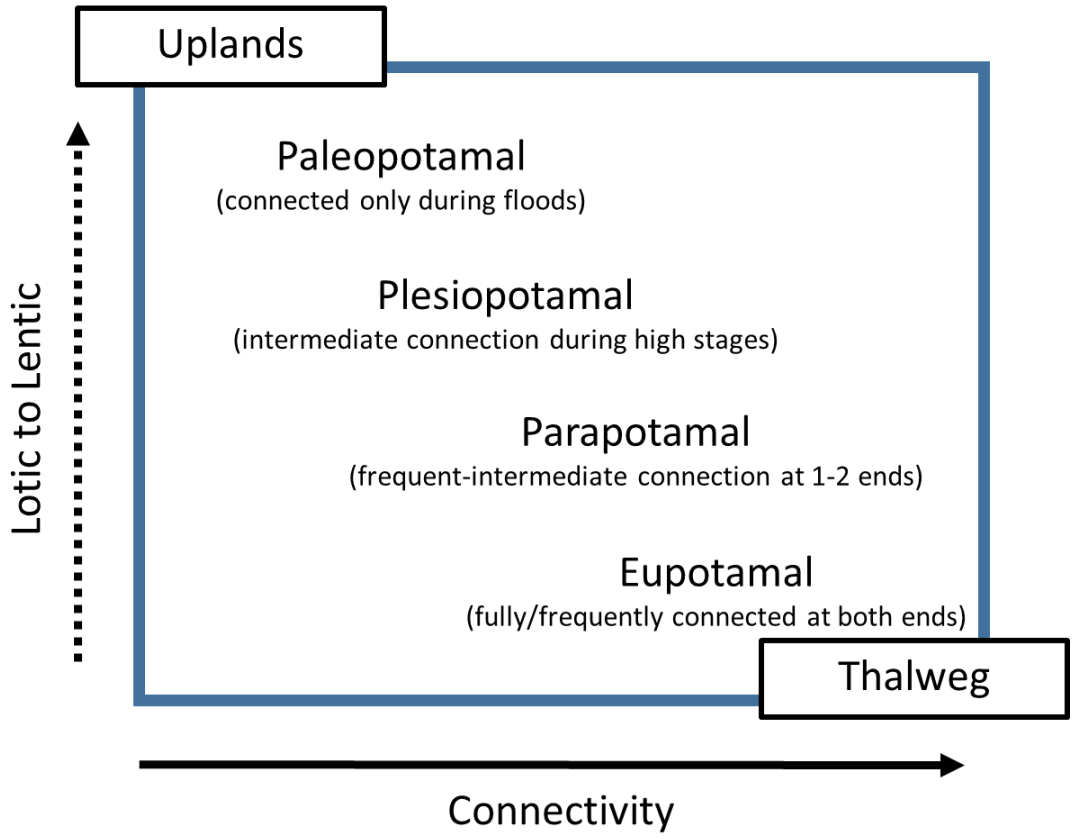

Figure 3.2. Habitat type and connectivity relative to the main channel. Modified from Ward & Stanford (1995).

Sampling and Processing

Eupotamal sites (secondary channels) were sampled using a benthic sled according to the methods outlined in Harrison et al. (*in press*). All other sites were sampled using either a petite Ponar grab or a pole-mounted Ekman grab according to manufacturer's (Wildco ©) instructions. The use of multiple gears was required because secondary channels cannot be sampled effectively with grab samplers due to high water velocities, and backwater habitats do not have the boat access required for the benthic

sled (Harrison et al., *in press*). To account for possible gear bias, samples were standardized as catch per unit effort (CPUE), rather than biomass or spatial abundance. At each site, three samples were taken according to a stratified random sampling design with the objective of acquiring samples fully representative of the habitat. Large sites (oxbows and secondary channels) were subdivided into multiple sites (i.e., upper, middle, lower). Samples were washed and sieved through 500 µm mesh in the field, placed in plastic sample bags in 80% EtOH, and returned to the laboratory in Vicksburg, MS, for counting and identification. Using an Olympus SZX16 stereo microscope and appropriate taxonomic keys (Epler 2001; Merritt et al. 2008; Morse et al. 2017; Pennak 1978; Thorp and Covich 1991), insects were identified to genus when possible. Early instars and Chironomidae were identified to family; mollusks captured live were identified to family; relict mollusks were not identified; aquatic worms were identified to subclass or family if possible.

At each site at the time of sampling, the following abiotic data were collected using a YSI Pro DSS: water temperature (°C), conductivity (µS/cm), dissolved oxygen (mg/L), pH, turbidity (NTU). Water velocity (cm/s) was measured at each site using a Marsh-McBirney, Inc. Flow-Mate Model 2000. Depth (m) was recorded for each sample using an on-board depth finder (Garmin GPSMAP 4212) or stadia rod.

Site Metrics and Data Analysis

Distance to the main channel was calculated for each sample as the shortest straight line distance from the sample's GPS location to the main channel water's edge as shown on 24 June 2012 National Agriculture Aerial Imagery (NAIP). As part of a larger

project, connection frequency was calculated for each site, following the methodology of Oliver et al. (2016). To determine connection frequency, the connection threshold (location and elevation where a water body first connects to the river) was first determined. For example, Desoto Lake connects when river water begins to flow over the weir at the lower end of the lake. Thus its connection threshold equals 130.3 ft. located at river mile (RM) 624.5. A second connection threshold at or near the opposite side/end of each water body was also located. When both connection thresholds are exceeded, water can be considered flowing through the site. For this study connection threshold was determined from bare earth elevation data gathered from 2005 and 2009 aerial LiDAR (Light Detection and Ranging), 2013 - 2016 bathymetric surveys, and for Graveyard, McWilliams, Old River Chute, and Jim Samples culvert bottom elevations. When these data were unavailable, on site observation and NAIP imagery (2003 - 2015) were used. The connection threshold was then converted to an equivalent water surface elevation (WSE) at the Helena gage using the following equation:

Conn. Threshold ft + ((Helena RM - Conn. Threshold RM)*avg. slope*5280 ft/mile)

The average river slope used was 0.00009 calculated by averaging the 2000-2015 daily slope, which encompasses a wide variety of water years while minimizing the influence of changing river bed. Slope was calculated by taking the Helena WSE gage reading minus Friars Point WSE gage reading or Fair Landing gage (chosen because of proximity to project area) reading divided by the distance between the two gages. Helena WSE gage readings were then compared to the Helena converted connection threshold to determine timing and frequency of surface-water connections. Connection frequencies

(approximations because they are based upon a comparison of a onetime measurement of the connection threshold elevation) were quantified in multiple ways (*see* Table 3.2).

Table 3.2. Calculated connection frequency metrics, measurement intervals, and variable abbreviations included in analyses.

Connectivity Frequency Metric	**Measurement Interval**	**Variable Abbreviation**
Single Connection Frequency = Percentage of days water surface level was greater than first connection threshold during a defined period.	3 months prior to sampling (0-91 days)	3SngConn
	6 months prior to sampling (0-182 days)	6SngConn
	12 months prior to sampling (0-365 days)	1yrSngConn
	Time since last major flood event (0 days-13 May 2011)	2011SngConn
Flow Thru Connection Frequency = Percentage of days when water surface level was greater than two connection thresholds, allowing water to flow through the site.	3 months prior to sampling (0-91 days)	3FTConn
	6 months prior to sampling (0-182 days)	6FTConn
	12 months prior to sampling (0-365 days)	1yrFTConn
	Time since last major flood event (0 days-13 May 2011)	2011FTConn
Number Days Disconnected = Number of consecutive days prior to the sampling day that site was disconnected from the river. Zero indicates site was connected on sampling day.	Disconnected at one connection threshold	NumSngDisconn
	Disconnected at both connection thresholds	NumFTDisconn
Number Days Connected** = Number of consecutive days during most recent connection event that site was connected to the river.	Connected at one connection threshold	NumSngConn
	Connected at both connection thresholds	NumFTConn
**While the majority of sites fit the original connectivity classification scheme (eupotamal-paleopotamal), some paleopotamal sites were actually connected more frequently than initially thought. Ad hoc groupings remained consistent throughout the study, whereas connection frequencies are more accurate quantifications of connectivity.		

Community composition and biodiversity metrics were analyzed using PRIMER (Plymouth Routines in Multivariate Ecological Research) software Version 7. Macroinvertebrate data were compiled into matrix format and an overall 4^{th} root transformation was applied to balance the contributions of rare and common taxa while still taking into account counts (Clarke et al. 2014). A resemblance matrix was calculated

to compare samples using the Bray-Curtis Similarity Coefficient and a dummy variable of 1 was included for proper measure of similarity/dissimilarity (1 – 0) between samples with few individuals (Clarke et al. 2006; Clarke et al. 2014). Non-metric multidimensional scaling (nMDS) was used to visualize the macroinvertebrate community in the context of connectivity. To highlight the taxonomic shifts across connectivity types, segmented bubble overlays were superimposed on the community nMDS plot. These taxa were selected using a Similarity Percentages (SIMPER) analysis (80% cutoff for low contributions), which outputs the typifying taxa in the defined connectivity group. Typifying taxa represented in multiple connectivity types were shaded in Figure 6 by their percent contribution to the connectivity type (Chapter 7, Clarke et al. 2014). For example, if a taxon was typifying for both plesiopotamal (9% contribution) and paleopotamal (32% contribution), it was shaded for the highest percentage, in this case paleopotamal. To test for differences in community structure, metric multidimensional scaling was performed on the resemblance matrix and bootstrap averages were calculated on the means. Influences of connectivity on macroinvertebrate communities were tested using a one factor (fixed effect = connectivity type) permutational multivariate analysis of variance (PERMANOVA), which operated on the 4^{th} root transformed resemblance matrix (Bray-Curtis similarity). This procedure produces a Pseudo-F statistic that is analogous to a univariate ANOVA F-statistic (Clarke et al. 2014; Costa et al. 2017; Weydmann et al. 2012). This test was followed by a pairwise test of differences in macroinvertebrate communities between connectivity types.

To analyze the association of connectivity types to each other based on abiotic parameters, a principal components analysis (PCA) was performed on a resemblance matrix constructed using Euclidian distance (Clarke et al. 2014), and included the following normalized variables: Site Area, Maximum Depth (Max. Depth), Connection frequencies (Sng3mthConn, Sng2011Conn, FT3mthConn, FT2011Conn, % time dry in year prior to sampling), distance from the main channel (Distance to River (m), surface turbidity (NTU), dissolved oxygen (DO), surface water temperature (Water Temp.), conductivity, and surface pH. These variables were selected from all available metrics using draftsman plots to identify and exclude highly collinear variables (correlation coefficients $> |0.95|$), primarily redundant connectivity metrics (Table 3.3).

For determination of the relationships between macroinvertebrate community structure and abiotic factors, a BEST (Bio-Env) analysis was performed on the 4^{th} root transformed macroinvertebrate sample resemblance matrix (Bray Curtis) and the normalized environmental resemblance matrix (Euclidian distance). This procedure executes a permutational comparison between the two matrices and outputs correlations of variables that best explain variability in the macroinvertebrate matrix, as well as a test statistic (Rho) and its statistical significance level (Clarke et al. 2014). For further insight into the effects of connectivity on taxonomic makeup of macroinvertebrate communities, stacked bar plots including average counts and richness were constructed for short term (3FTConn) and long term (2011FTConn) connection frequencies. Connection frequencies were grouped into low, intermediate, and high connection frequencies based on sites sampled in the study. There were no sites with true “intermediate” long term

connection frequencies included in this study, so eupotamal sites with 73.3-75.8% connection frequency since 2011 were included as intermediates.

Table 3.3. Variables included in Principal Components Analysis and eigenvectors for PCs 1-5 (86% variance accounted for).

Variable	PC1	PC2	PC3	PC4	PC5
Site Area (m)	0.13	-0.503	0.158	-0.143	0.04
Max. Depth (m)	0.386	0.025	-0.034	0.058	-0.1
Water Temp.	0.074	0.201	0.651	-0.302	-0.154
Conductivity	0.258	-0.248	-0.068	-0.435	-0.541
pH	-0.149	0.105	0.53	0.536	-0.458
D.O.	-0.144	-0.3	-0.387	0.337	-0.528
Turbidity	0.229	0.279	-0.171	0.178	0.084
Distance to River	-0.052	-0.491	0.213	0.096	0.323
Sng3mthConn	0.376	-0.222	0.102	-0.013	0.001
FT3mthConn	0.367	0.239	-0.035	-0.036	0.001
Sng2011Conn	0.4	-0.15	0.04	0.144	-0.041
FT2011Conn	0.36	0.263	-0.118	0.1	-0.075
% Time Dry 1 year prior to sampling	0.314	-0.163	0.116	0.471	0.256

Results

During the course of this study, a total of 231 samples were collected, including >90 unique taxa (Appendix B). There were significant differences in macroinvertebrate community structure between connectivity types (Pseudo-F= 15.826, p=0.001; Table 3.4) resulting in measurable differences in the spread of the sample resemblance (Bray-Curtis similarity) in Figure 3.3. Eupotamal sites separated from more disconnected sites along MDS1, while paleopotamal sites separated along MDS2. A stacked bar plot (Figure 3.4) highlights the differences in taxonomic composition occurring across connectivity types. A wider variety of taxa were captured in the eupotamal sites compared to the more disconnected sites. Disconnected sites (parapotamal – paleopotamal) shared the majority

of taxa, but in different relative proportions. Differences in community composition between habitat types is visible in the nMDS ordination labeled by connectivity type (Figure 3.5). The typifying taxa driving the differences in community composition across habitat types (SIMPER) are highlighted in the segmented bubble plot overlay in Figure 3.6.

Table 3.4. Pairwise PERMANOVA (Permutational Analysis of Variance) by connectivity type of 4th root transformed macroinvertebrate resemblance matrix (Bray-Curtis Similarity).

Connectivity types (Groups)	T	P (perm)	Unique Permutations
Eupotamal, Parapotamal	4.3654	0.001	999
Eupotamal, Plesiopotamal	5.2481	0.001	999
Eupotamal, Paleopotamal	3.805	0.001	997
Parapotamal, Plesiopotamal	2.7862	0.001	999
Parapotamal, Paleopotamal	2.9942	0.001	999
Plesiopotamal, Paleopotamal	2.9396	0.001	998

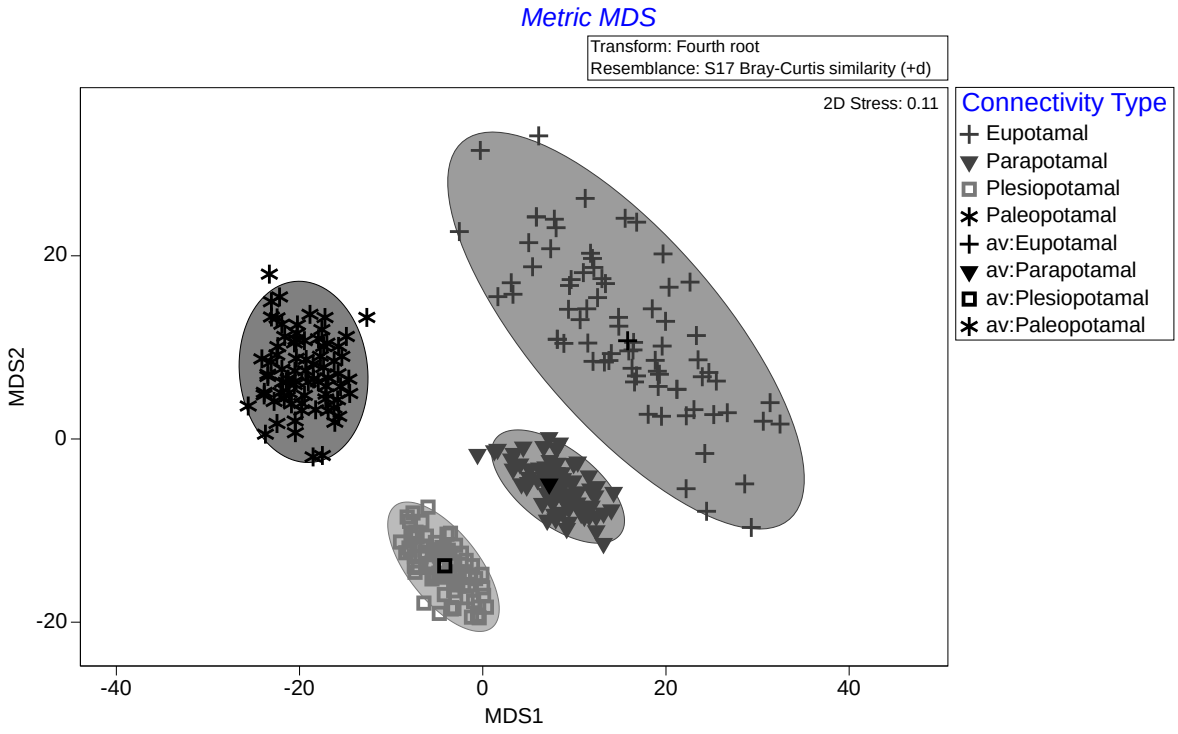

Figure 3.3. mMDS ordination of macroinvertebrate samples' Bray-Curtis Similarity Coefficient and 75 bootstrap averages. Mean bootstrapped averages for each connectivity type are represented by black symbols. Clouds represent the 95% confidence interval for means.

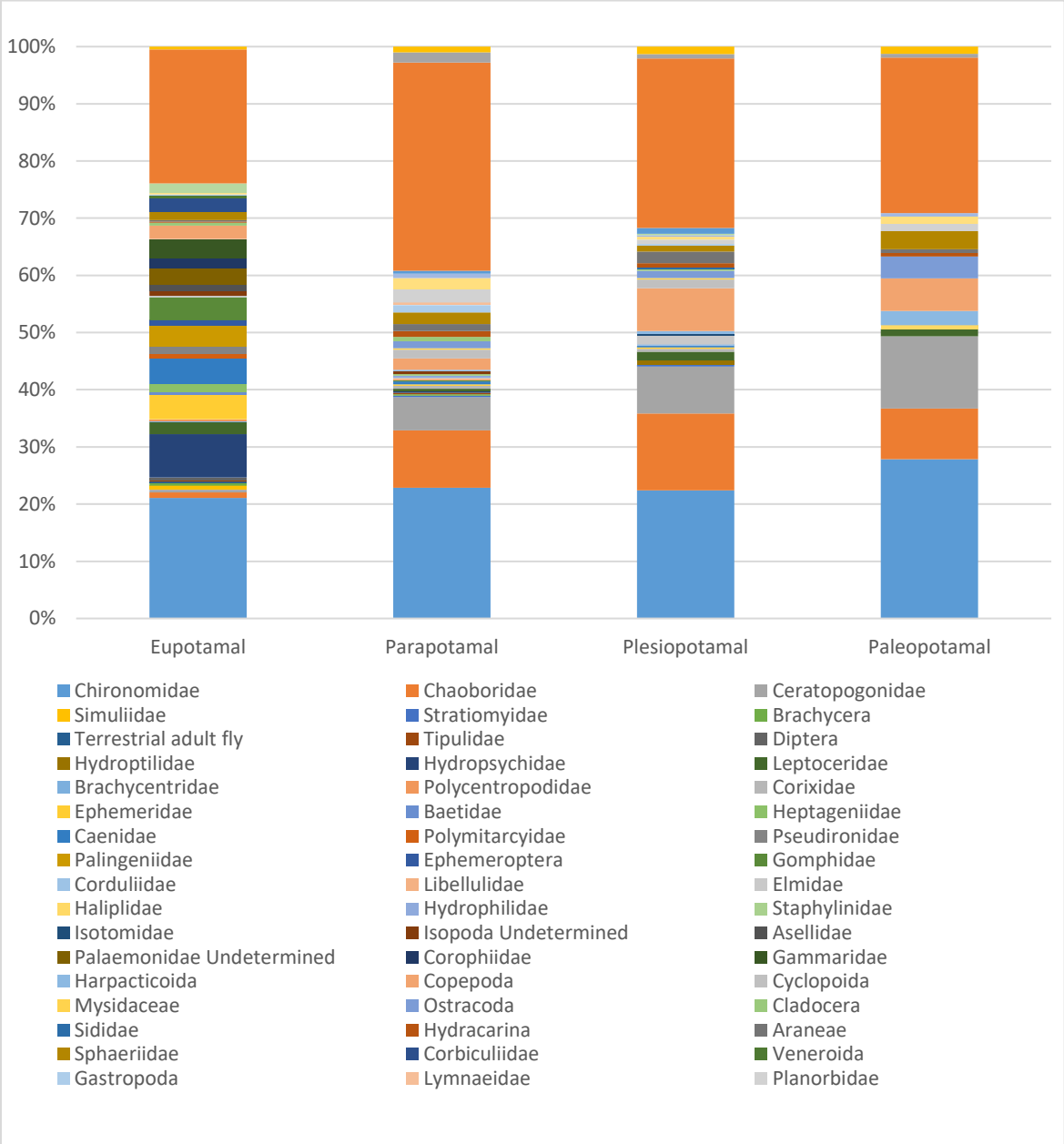

Figure 3.4. 100% Stacked bar plot with combined taxa from each connectivity type represented as percentages. Taxonomic groups are collapsed into families or higher unit to reduce legend entries.

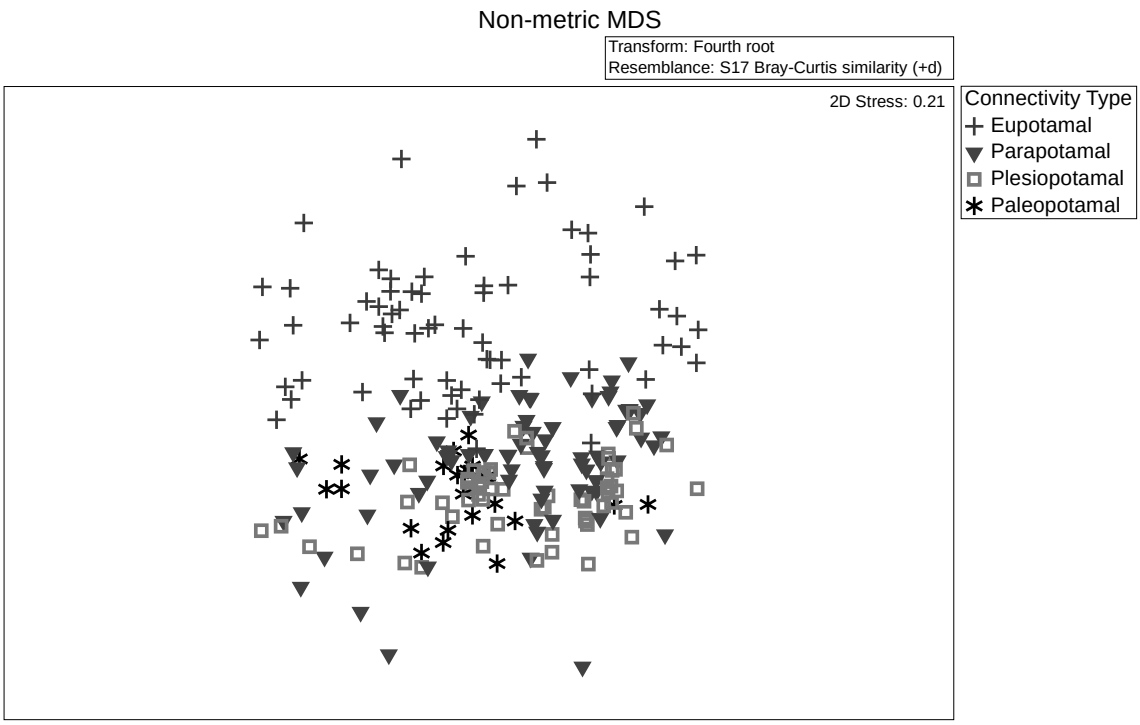

Figure 3.5. nMDS ordination of macroinvertebrate sample resemblances calculated using Bray-Curtis Similarity Coefficient and labeled by connectivity type.

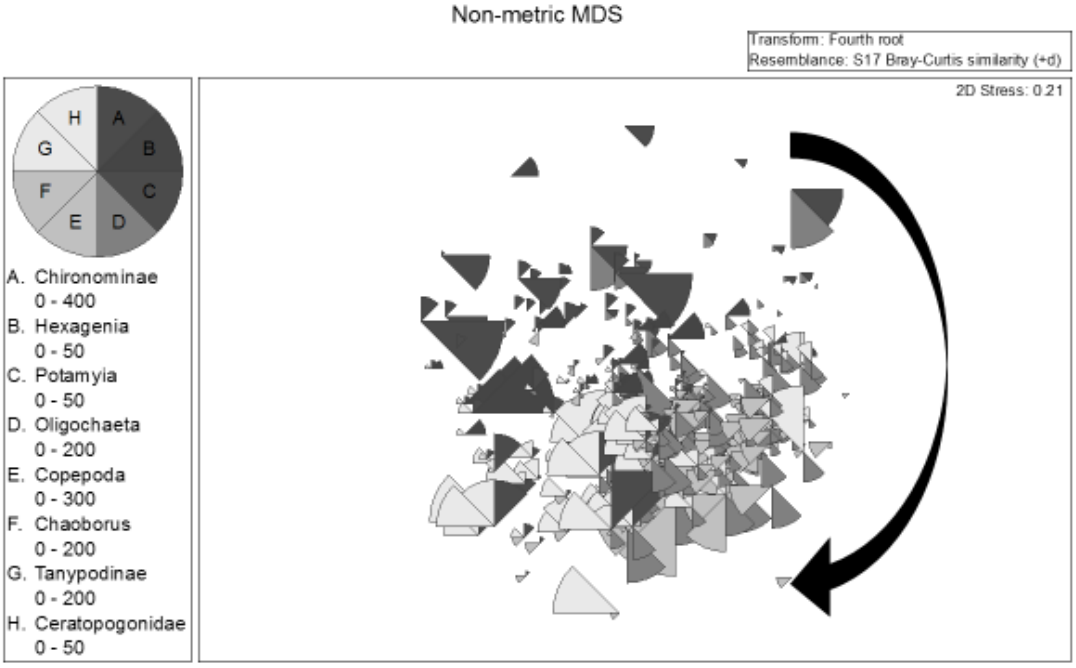

Figure 3.6. nMDS ordination of macroinvertebrate sample resemblances calculated using Bray-Curtis Similarity Coefficient overlaid by segmented bubbles representing relative abundances of dominant typifying taxa for each connectivity type.

Connectivity types (sites) separated from each other based on abiotic parameters (Figure 3.7), with 86.4% of the variation captured by PC1-PC5. Eupotamal and parapotamal sites separated from each other along PC1 and PC2 based on turbidity, connection frequencies, and water quality, while plesiopotamal and paleopotamal sites separated from other connectivity types but not each other. The BEST procedure resulted in significant (Rho = 0.477, $p < 0.01$) relationships between environmental conditions and macroinvertebrate community structure. Turbidity and historic connection frequency were the environmental variables most highly correlated with the macroinvertebrate community.

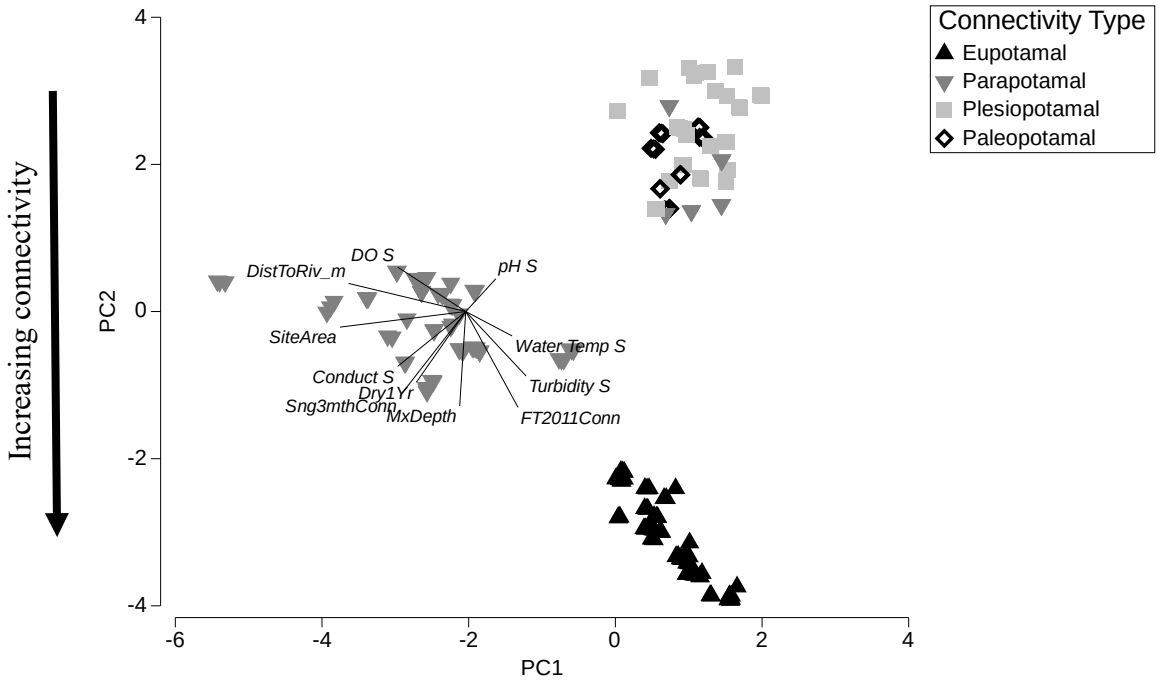

Figure 3.7. Principal components analysis of environmental metrics labeled by site connectivity type.

To further elucidate the influence of connection frequency on macroinvertebrate communities, two time scales – long term and short term were chosen for analysis.

Stacked bar plots represent the number of taxa present at low, intermediate and high connection frequencies during each time frame (Figures 3.8-3.9). At both the three month and long term time scales, highest numbers of taxa were present at low connection frequencies (0-10.5%), followed by high connection frequencies (90.0-100%). Intermediate connection frequencies (22-75.8%) were lower in taxonomic richness at both time scales. Average numbers of individuals in samples was highest at low and intermediate connection frequencies at the three month scale and lowest at high connection frequencies Figure 3.8. At the long term time scale, samples from sites with low connection frequencies had on average higher numbers of individuals per sample than samples from sites with high or intermediate connection frequencies (Figure 3.9).

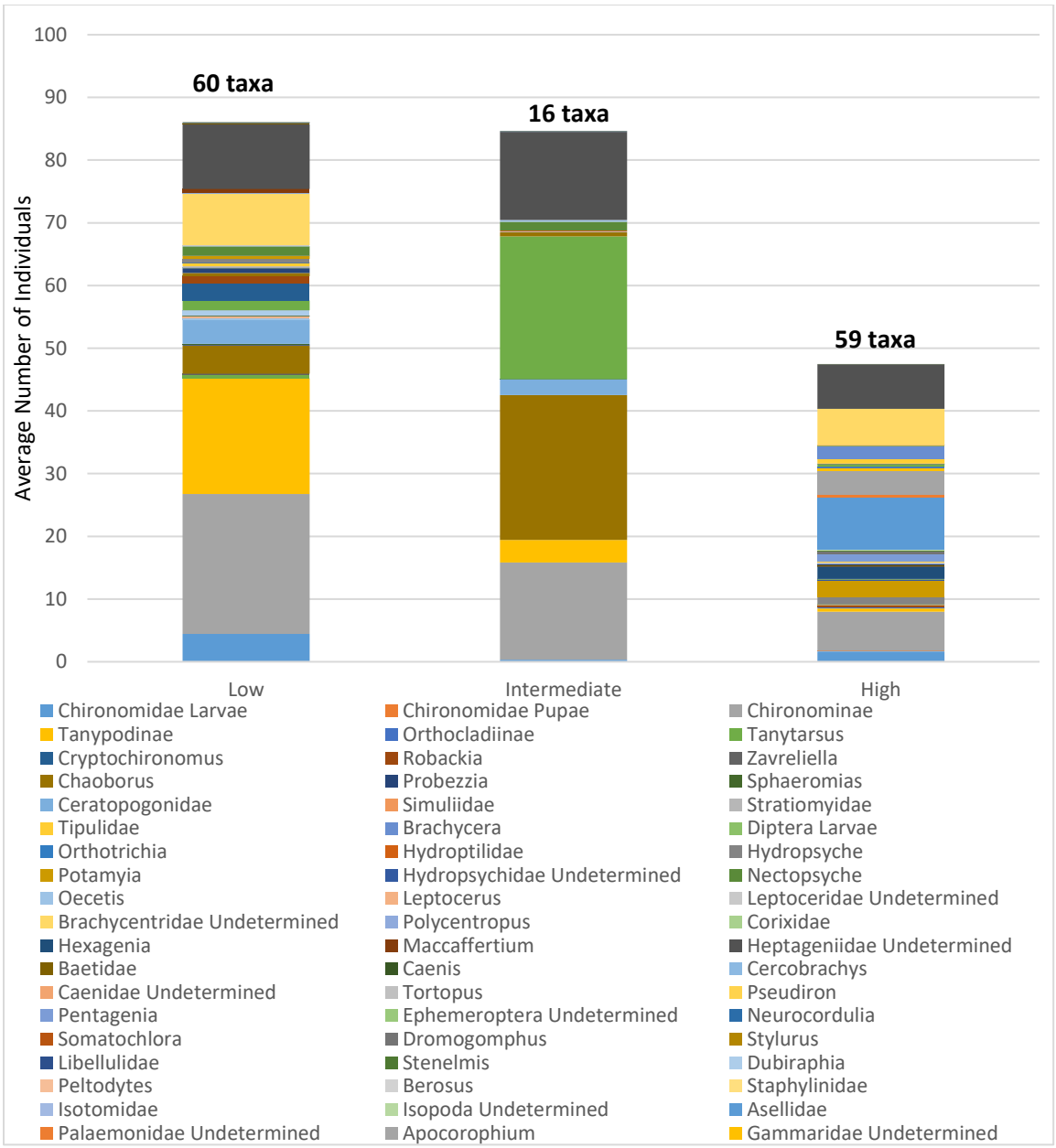

Figure 3.8. Stacked bar plot representing numbers of taxa present at different connection frequencies over the 3 months prior to sampling and average number of individuals per sample at each connection frequency. Low = 0% connection, Intermediate = 22-40.7% connection, High = 100% connection. Note: some taxa were present at multiple sites with different connection frequencies.

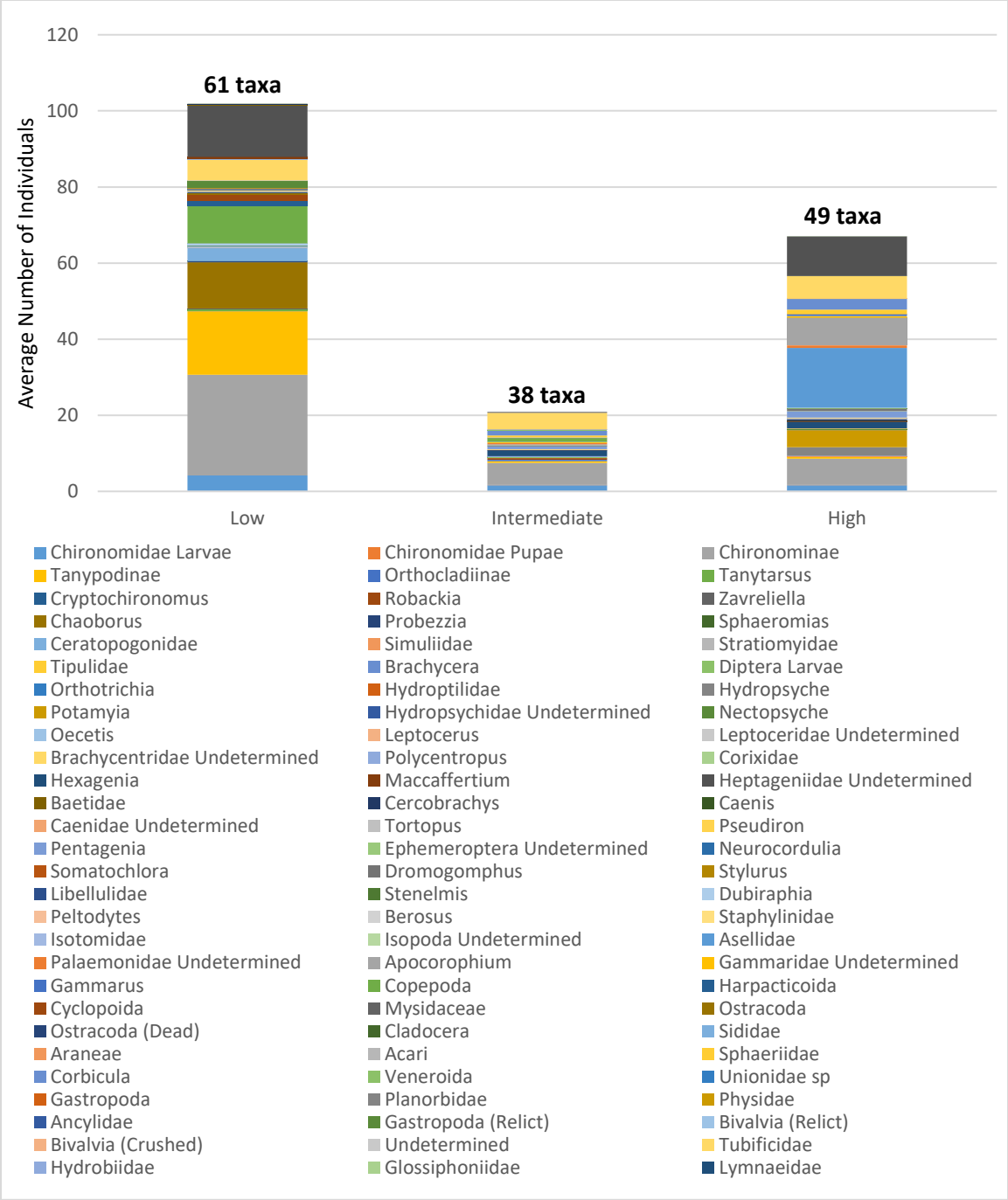

Figure 3.9. Stacked bar plot representing numbers of taxa present at different long-term (since last major flood event [2011]) connection frequencies and average number of individuals per sample at each connection frequency. Low = 0-10.5% connection, Intermediate = 73.3-75.8% connection, High = 90.9-100% connection. Note: some taxa were present at multiple sites with different connection frequencies.

Discussion

Gaining insight into the factors governing community structure and function is critical to the understanding of ecological function of the system as a whole – how it works, its capabilities, and its value. Large river-floodplain ecosystems are naturally a mosaic of aquatic habitats home to a unique floral and faunal assemblage, ranging from forested vernal pools to the swift main channel of the river. All of these habitat types have in common their linkage with the river and are different in their connectivity to the river. Determining how connectivity influences biotic communities is important for many reasons, including gaining predictive power for community assemblages, understanding the response of populations following extreme flood events, monitoring baselines, and making management and restoration decisions about priority habitats for conservation of species of interest. Both lotic and lentic macroinvertebrates are important contributors to aquatic ecosystems. As secondary producers, they utilize primary producers for nutrition and become food for higher aquatic and terrestrial consumers, intimately linking them to the nutrient and trophic cycles of the system. A community level perspective is particularly useful in identifying what structures the macroinvertebrate assemblage in different habitats, and understanding these factors is a necessary first step for management of both the physical habitat and the biological integrity of this system.

Our results indicate that habitat types (eupotamal – paleopotamal) separated from each other based on connectivity parameters, such as suspended sediment load (turbidity) and connection frequencies, as well as water quality metrics such as dissolved oxygen levels, conductivity, pH, and conductivity. These differences are likely due to the

increase in primary productivity in backwaters, along with other physio-chemical changes occurring as suspended sediments precipitate from the water column upon disconnection, which has been observed in floodplain lakes in the Lower Mississippi River (Pongruktham and Ochs 2015), and is predicted by the Flood Pulse Concept, River Ecosystem Synthesis, and River Productivity Model (Junk et al. 1989; Thorp and Delong 1994; Thorp et al. 2006).

This study also provides evidence in partial support of other studies concluding that macroinvertebrate communities are influenced by connectivity (Paillex et al. 2009; Pander et al. 2018). Communities present in each habitat type were distinct from each other. Although habitat types ranging from eupotamal to paleopotamal, particularly backwaters, had some overlap in taxa presence, relative proportions and abundances differed. This is reflected in both the 100% stacked bar plot (Figure 3.4), which highlights the contribution of various taxa to the community present as well as the nMDS bubble plot (Figure 3.6), which highlights shifts in typifying taxa along this connectivity gradient.

Turbidity and long-term connection frequency were the abiotic parameters most highly correlated with macroinvertebrate community resemblance, reflecting both current and historic effects, respectively. When short term (3 months) and long term (since 2011) time scales were investigated, stark differences were found in the taxonomic richness present at different connection frequencies. Taxonomic richness is one of many metrics used to assess the value of habitats, and while it should not be used in isolation, it can be an indicator of environmental heterogeneity, disturbance, and niche availability (Hutson

1979; MacArthur and Wilson 1967; Ricklefs 1987). Sites that were highly connected or highly disconnected hosted a greater number of taxa at both time scales, while intermediately connected sites hosted fewer taxa than either extreme, indicating a dependence on habitat stability for community permanence. In this case, intermediate connectivity with frequent connection and disconnection is likely a disturbance where many species of macroinvertebrates lack the environmental stability necessary to maintain position and survive. While this seems counter to the intermediate disturbance hypothesis (Connell 1978; Townsend et al. 1997), it is probably only partially so, because only infrequent and intermediately frequent disturbances were investigated. In addition, two distinct communities (lotic and lentic) were represented, and disturbances to each would be opposite: disturbance to the lotic community would be loss of connectivity, while disturbance to the lentic community would be connection. However, parapotamal sites, which are intermediately connected to the main river channel (oxbows and an abandoned chute in this study), supported fewer taxa than either the highly connected or disconnected sites, and the taxa present were generalists adapted to both lotic and lentic environments. As found in other studies, the changes in taxonomic presence/absence across varying connection frequencies represent a shift from a fully lentic community characterized by rheophobic taxa such as aquatic Coleoptera, Hemiptera, and Odonata, to a fully lotic community represented by Trichoptera, Ephemeroptera, and rheophilic Diptera (Paillex et al. 2009).

While taxonomic richness is lower at intermediate connection frequencies, the same was not consistently true for numbers of individuals per sample. In fact, in the short

term (3 months), intermediately connected sites had roughly the same average numbers of macroinvertebrates per sample, highlighting their importance in nutrient cycles and food webs. In the long term, intermediate connectivities were represented by lower average counts of individuals per sample, although none of our study sites had long term connection frequencies between 11 -73%, so these numbers have limited interpretive value.

In conclusion, results from this research highlight the relationships between large scale river-floodplain connectivity and macroinvertebrate community structure. It is clear that communities differ at different frequencies of connection to the main channel, with more isolated habitats hosting a lentic community, and highly connected sites a lotic community. Intermediately connected sites host a generalist macroinvertebrate assemblage with the ability to survive in both flowing and standing water conditions. This, along with other recent studies, highlights the need for water resource managers to maintain a gradient of connectivity within the Lower Mississippi River batture, as well as other large river-floodplain systems for conservation of macroinvertebrate diversity, which will benefit top-down and bottom-up trophic cycles for a multitude of organisms (Pander et al. 2018). In particular, efforts should be taken to (1) quantify available habitat and measure connectivity, and (2) create and maintain a gradient of connectivity, including fully lentic (paleopotamal) and fully lotic (eupotamal) habitats in order to maximize biodiversity in this and other heavily engineered river-floodplain systems. In addition, other organismal groups should be included in future study of the Lower

Mississippi River, in order to achieve a holistic understanding of the entire ecosystem (Paillex et al. 2009; Pander et al. 2018).

Acknowledgements

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CHAPTER IV:

MACROINVERTEBRATE RESPONSE TO SECONDARY CHANNEL CONNECTIVITY IN THE LOWER MISSISSIPPI RIVER

ABSTRACT

Secondary or side channels are a common habitat feature in large rivers, marked by the presence of an instream island. In these channels, flow velocities are reduced, making them important areas of refugia for riverine organisms. In the free-flowing Lower Mississippi River, secondary channels are numerous and provide a substantial amount of riverine habitat, comprising roughly one-third the total length of this 1500 km reach. Availability of this habitat for use by riverine organisms is critical in their life cycles, because unlike the main channel, which is heavily engineered for navigation and flood control, secondary channels retain more natural habitat features including natural steep banks and a higher proportion of riparian interface. In this system, however, most secondary channels are disconnected periodically from the main channel by dikes at their upstream opening. When river stages fall below the top of the dike, surface flow into the secondary channel ceases, transforming them from lotic to lentic, and in some cases becoming completely dry. The river stage at which channels become disconnected from main channel flow varies from channel to channel, and within the Lower Mississippi River, there are channels that span a gradient of hydrological connectivity with the main channel. This connectivity gradient makes secondary channels an ideal stage for the study of ecological effects of connectivity on the biota. In this study, macroinvertebrate communities of secondary channels along this gradient of connectivity were investigated. Results indicate a legacy effect of seasonal disconnection on riverine communities, particularly for maintenance of a lotic macroinvertebrate assemblage. These results

address the impacts of reduced connectivity and habitat stability on organisms with limited mobility and complex life cycles. In addition, this research will help guide ongoing and future secondary channel restoration efforts such as dike notching, to ensure channel conditions are suitable and bioavailable for a suite of riverine organisms.

Introduction

Habitat connectivity is an essential component of naturally functioning ecosystems for the maintenance of natural processes, such as trophic interactions, nutrient processing, and dispersal of individuals. Habitat connectivity is especially important in net heterotrophic systems such as large rivers (Cloern 2007; Pongruktham and Ochs 2015). Several prevalent theories (e.g., River Continuum Concept, Flood Pulse Concept, Riverine Ecosystem Synthesis) suggest the importance of resource input from neighboring systems in maintaining biodiverse aquatic ecosystems (Amoros and Bornette 2002; Junk et al. 1989; Thorp et al. 2006; Vannote et al. 1980). In river-floodplain systems, habitat connectivity occurs via hydrological connectivity, or the multidirectional movement of water between habitats, which is responsible in part for the ecological integrity of the system (Amoros and Bornette 2002).

Human modification of waterways dates back centuries. We have altered the form and function of every river system worldwide, disrupting longitudinal, lateral, and vertical connectivity (Amoros and Bornette 2002; Arthington 2012). Modification of the Mississippi River Valley began in the 1700s when settlers began levee construction for flood protection. Modifications have continued dramatically and steadily for flood control as well as to maximize efficient use of the Mississippi River and its tributaries for

commercial navigation (Baker et al. 1991; Killgore et al. 2014; Morris 2012). These modifications have come at a great expense, and although many effects are unknown, they are arguably most costly at the ecological level (AWI 2015).

Loss of connected floodplain (e.g., 90% reduction in the LMR) due to levee construction, the environmental movement, and scientific evidence of river species and habitat decline has catalyzed restoration efforts worldwide targeting in-channel and batture habitat (Baker et al. 1991; Buijse et al. 2002; Gumiero et al. 2013; Hein et al. 1999; Killgore et al. 2014, Tockner and Stanford 2002). One of the most common anthropogenic disturbances to the LMR channel are "river-training" structures, including dikes, closing structures, hardpoints, and chevrons (Baker et al. 1991; Killgore et al. 2014). These stone structures function to direct flow into the main river channel, creating a self-scouring navigation channel, thereby reducing the need for costly dredging (Baker et al. 1991). However, at low river stages, closing structures block main channel surface flow into the upstream end of secondary channels. Secondary channels disconnected from the main river flow may be transformed for various lengths of time into a series of isolated pools, or become completely dry. This shift from a lotic to lentic environment results in physiochemical changes in the water and sediments (Chapter 5). In this system, these changes are considerable because there are more than 100 naturally occurring secondary channels (marked by the presence of an island), occurring on average every three river miles and comprising roughly one-third the length of the LMR (Baker et al. 1991; Killgore et al. 2014; Figure 4.1).

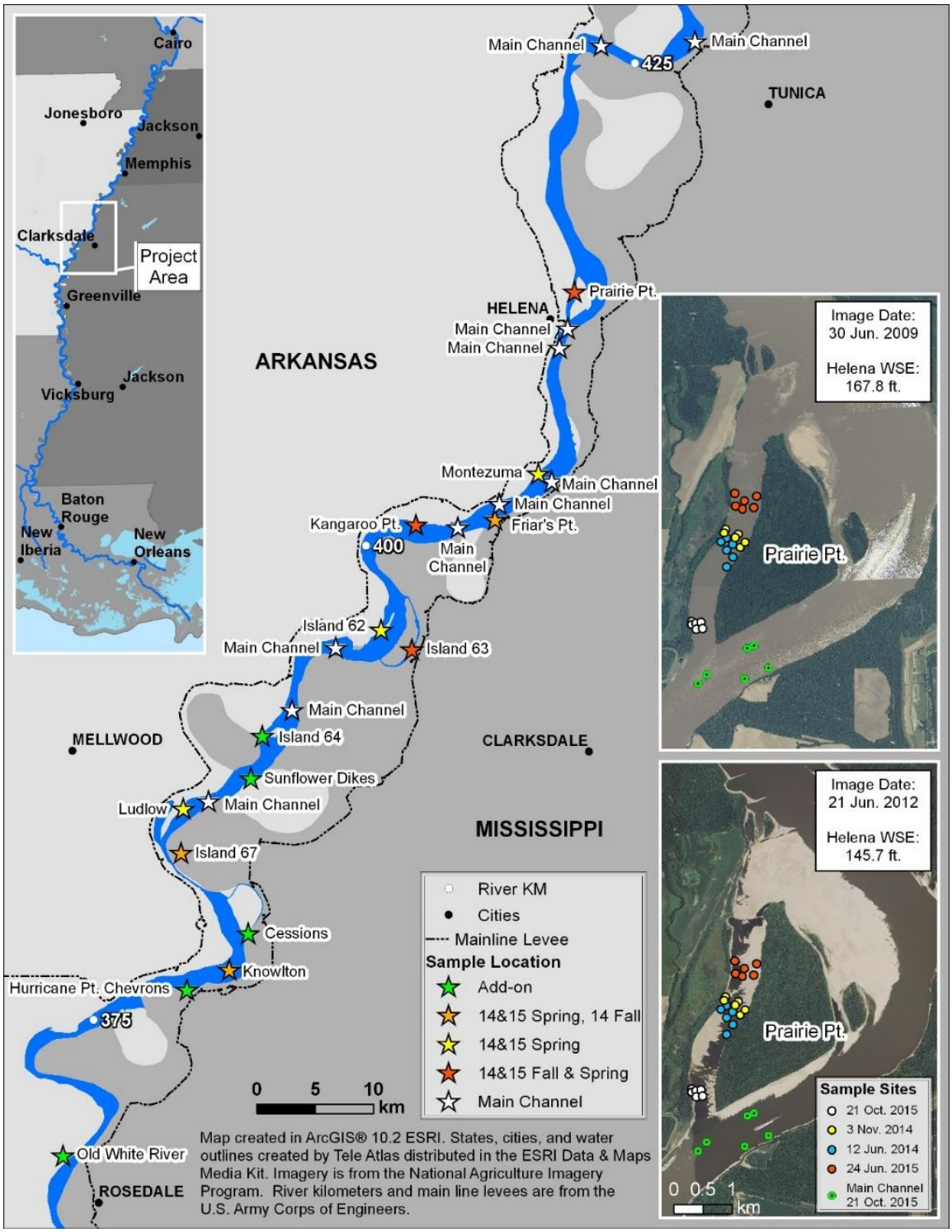

Figure 4.1. Study area within the Lower Mississippi River and example of secondary channel at a high river stage (image date 30 June 2009) and low river stage (image date 21 June 2012).

To remain compliant with the biological opinion for the USACE Channel Improvement Program Mississippi River and Tributaries Project, efforts must be taken by the USACE to maintain at least 84 secondary channels with flow at moderate river stages for use by the three endangered species inhabiting the LMR (i.e., Interior Least Tern, Pallid Sturgeon, and Fat Pocketbook Mussel) (USFWS 2013). This includes designing new dikes and retrofitting existing closure dikes with V-shaped "notches" to achieve flow during lower water stages, a practice that began in 2006. Notching of existing dikes has/is been conducted by the Lower Mississippi River Conservation Committee (LMRCC) and the U.S. Army Corps of Engineers (USACE) and so far, notches have been cut into dikes in more than 50 secondary channels, and additional notches are scheduled for the future (USACE Memphis District, pers. comm.; LMRCC, pers. comm.).

Despite these ongoing efforts, we are limited still in our understanding of how riverine organisms are affected by periodic loss of flow, and there is an eminent need for research at multiple organismal scales. Unfortunately, we lack pre-disturbance data. However, we can analyze the persistence and distribution of biotic communities to establish floristic/faunistic baselines that can be used as indicators of long-term and short-term environmental changes. Aquatic macroinvertebrates, especially insects, are particularly good indicators of long-term and short-term habitat and water quality (Flotemersch et al. 2006a,b). For instance, (1) many benthic macroinvertebrates are relatively stationary, (2) taxonomic groups respond differently to environmental stressors, (3) species often have complex life cycles of a year or more, (4) they occupy a wide variety of niches (e.g., habitat, feeding, behavioral), (5) they are present in all freshwater habitat types, (6) they are integral components of aquatic and terrestrial food webs and

nutrient cycles, and (7) they can be collected and identified easily with proper training (Barbour et al. 1999; Flotemersch et al. 2006a,b; Merritt et al. 2008).

To gain understanding into the effects of periodic loss of flow connectivity on riverine organisms, we evaluated macroinvertebrate communities in channels varying in degree of flow connectivity over a period of two years. The primary objective of this study was to answer the following question, "Is there a measurable biotic response to a gradient of connectivity?"

Methods

Site Selection & Establishing Connectivity

A total of 14 secondary channels (Appendix A) within a 160 km reach of the Lower Mississippi River (Rkm 1110-949, RM 690-590) were sampled between June 2014 and October 2015. During high river stages (June 2014, 2015), 9 secondary channels were repeatedly sampled, and all were fully connected to the main channel (Table 4.1). In November 2014, due to low water, only 6 of the original 9 secondary channels were accessible due to disconnection at both the upstream and downstream channel ends. In October 2015, due to extremely low water, only 3 of the original 9 secondary channels were accessible, so samples were taken at an additional 5 secondary channels (add-on sites; Table 4.1). Sites were initially selected based on their proximity to a boat launch, to each other (i.e., all accessible during a three-day sampling window), and their level of flow connectivity to the main channel. Main channel flow connectivity occurs when water begins flowing into the upstream end of a secondary channel usually over a closing structure or associated sandbar. Flow connectivity was determined by

locating the flow threshold, location, and elevation where water begins flowing through a secondary channel. Flow thresholds were established in two ways: (1) using historic aerial photography (Google Earth) and (2) closure dike elevation (Memphis District Navigation Bulletin 2013). This was followed by post hoc in-depth analysis of 2005 to 2015 NAIP imagery and USACE acquired bathymetric transect data from 2004, 06, 08, 10, 11, and 13. Imagery were used to identify the channel or low spot in a closing structure where water first flowed into the upstream end of the secondary channel. The water surface elevation at the secondary channel in each image was interpolated from that date's water surface elevation (WSE) at the Helena and Arkansas City gage by using the following equation:

$$\text{Helena WSE ft.} - \left(\text{Helena RM} - \text{Threshold RM}\right) * \left(\frac{\text{Helena WSE ft.} - \text{Ark City WSE ft.}}{\text{Helena RM} - \text{Ark City RM}}\right)$$

Image water surface elevations and the elevations of the bathymetric transect points falling within flow threshold locations were used to determine the approximate flow threshold elevation. Where there were differences in the original and post hoc flow thresholds, field observations (dike exposure, secondary channel access, water velocity, substrate composition) were used to determine a final flow threshold (Figure 4.2). Once the flow threshold was established for each sample and site, legacy flow (i.e., percentage of time flowing) was calculated for 3-months, 6-months, and 1-year prior to sampling. Flow on day of sampling was identified in three ways: visual inspection, water velocity, and substrate composition/sediment type.

Table 4.1. Sampling dates and sites; "Planned" indicates part of original sampling plan, "Add-on" indicates channel was added due to inaccessibility of planned sites; "Connected" indicates if channel was connected to main channel at time of sampling.

Season	Year	Date	Site	Planned	Add-on	Connected	Connectivity Threshold (ft)
Spring	1	6/11/2014	Island 62 Secondary Channel	X		X	154.1
Spring	1	6/11/2014	Island 63 Secondary Channel	X		X	144.72
Spring	1	6/11/2014	Island 67 Secondary Channel	X		X	154
Spring	1	6/11/2014	Knowlton Secondary Channel	X		X	152
Spring	1	6/11/2014	Ludlow Secondary Channel	X		X	152.8
Spring	1	6/12/2014	Friars Point Secondary Channel	X		X	160.5
Spring	1	6/12/2014	Kangaroo Point Secondary Channel	X		X	152.69
Spring	1	6/12/2014	Main Channel (3 sites)	X		X	-
Spring	1	6/12/2014	Montezuma Secondary Channel	X		X	156.7
Spring	1	6/12/2014	Prairie Point Secondary Channel	X		X	156.76
Fall	1	11/3/2014	Friars Point Secondary Channel	X			150
Fall	1	11/3/2014	Main Channel (2 sites)	X		X	-
Fall	1	11/3/2014	Prairie Point Secondary Channel	X			156.76
Fall	1	11/4/2014	Island 67 Secondary Channel	X		X	154
Fall	1	11/4/2014	Kangaroo Point Secondary Channel	X			152.69
Fall	1	11/4/2014	Knowlton Secondary Channel	X			152
Fall	1	11/4/2014	Main Channel	X		X	-
Fall	1	11/5/2014	Island 63 Secondary Channel	X		X	144.72
Spring	2	6/23/2015	Island 62 Secondary Channel	X		X	154.1
Spring	2	6/23/2015	Island 63 Secondary Channel	X		X	144.72
Spring	2	6/23/2015	Kangaroo Point Secondary Channel	X		X	152.69
Spring	2	6/24/2015	Friars Point Secondary Channel	X		X	160.5
Spring	2	6/24/2015	Main Channel	X		X	-
Spring	2	6/24/2015	Montezuma Secondary Channel	X		X	156.7
Spring	2	6/24/2015	Prairie Point Secondary Channel	X		X	156.76
Spring	2	6/25/2015	Island 67 Secondary Channel	X		X	154
Spring	2	6/25/2015	Knowlton Secondary Channel	X		X	152
Spring	2	6/25/2015	Ludlow Secondary Channel	X		X	152.8
Spring	2	6/25/2015	Main Channel (2 sites)	X		X	-
Fall	2	10/20/2015	Island 63 Secondary Channel	X			144.72
Fall	2	10/20/2015	Island 64 Secondary Channel		X		145.4
Fall	2	10/20/2015	Kangaroo Point Secondary Channel	X			152.69
Fall	2	10/20/2015	Sunflower Dikes Secondary Channel		X		145
Fall	2	10/21/2015	Main Channel (3 sites)	X		X	-

Fall	2	10/21/2015	Prairie Point Secondary Channel	X			156.76
Fall	2	10/22/2015	Cessions Secondary Channel		X	X	142
Fall	2	10/22/2015	Hurricane Point/Chevrons/ Dennis Landing		X		143.08
Fall	2	10/22/2015	Old White River Secondary Channel		X	X	134.8

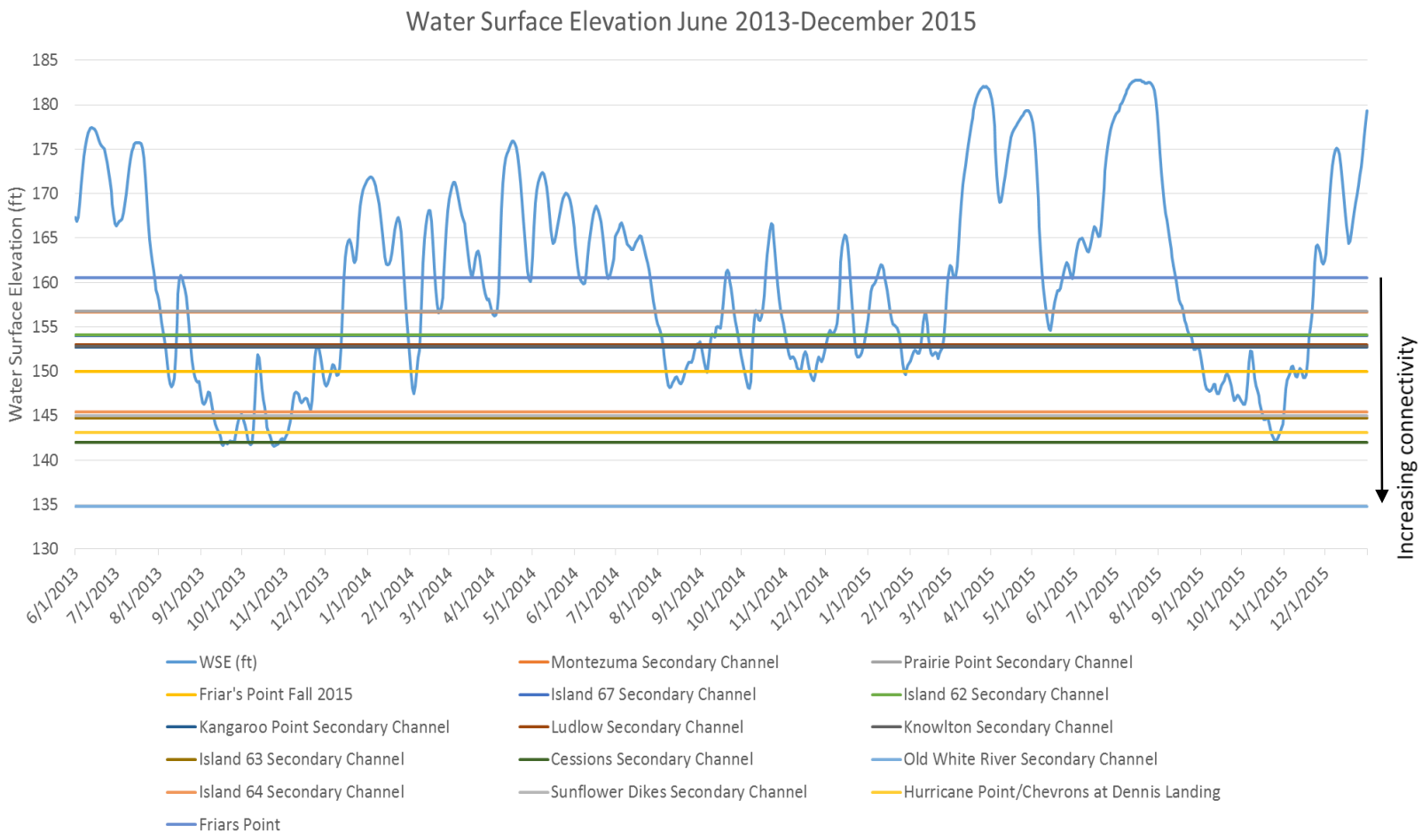

Figure 4.2. Mississippi River Hydrograph (water surface elevation at Helena, AR gage) and secondary channel connection thresholds (horizontal lines).

Procedures

Six samples were taken at each site using a benthic sled (*see* Harrison et al. *in press* [Chapter 2] for methods). The middle region of the secondary channel was targeted in order to avoid local upstream and downstream effects of dikes and the main river channel (Appendix A). At low water stages, the six replicate samples were taken where accessible, as the middle portion of the channel was sometimes dry. Benthic sled sampling locations were chosen based on a stratified random sampling design, with two samples taken along the right descending bank, two in the middle of the channel, and two along the left descending bank. The same sampling design was used for control (fully connected) sites (i.e., main channel). Three main channel sites were sampled at each event at locations without influence of secondary channels or tributary confluences. Environmental data, including water temperature, dissolved oxygen concentration, pH, conductivity, oxidation-reduction potential, and turbidity were taken in the mid-point of each site using a YSI Pro DSS, just below the water surface and just above the bottom substrates. Surface water velocity (cm/s) was measured at the midpoint of each sampling area using a Marsh-McBirney, Inc. Flow Mate Model 2000. GPS coordinates, water depth, and distance sampled were measured using an on-board Garmin GPSMAP 4212.

Upon retrieval of the benthic sled, samples were pre-processed on board, according to the methods outlined in Harrison et al. (*in press*). Samples were picked, sorted, and identified to the lowest possible taxonomic level in the laboratory at the USACE Engineer Research and Development Center (ERDC), Vicksburg, MS, using an Olympus SZX16 stereo microscope and an Olympus BX43 compound microscope and

taxonomic keys (Edmunds et al. 1976; Epler 2001; Merritt et al. 2008; Morse et al. 2017; Pennak 1953; Stewart and Stark 2002; Thorp and Covich 1991; Wiggins 1996).

A sediment sample was retained from each sample, stored in a sterile 50-mL centrifuge tube, and placed on ice for transport to the laboratory where it was frozen at -60°C. For processing, sediment samples were dried overnight at 30°C and placed in desiccation chambers. Loss on ignition (LOI) was used to measure the sediment's percent organic matter and microsieves were used to calculate average particle size. To calculate LOI, a known amount of sediment (0.00001 g) was placed in a 550°C muffle furnace for 2 hours and then re-weighed to determine the amount of organic matter lost during combustion (Ball 1964; Dean 1974; Heiri et al. 2001). Sediments were sieved through a microsieve stack with mesh sizes of 2 mm, 0.5 mm, 0.25 mm, 0.125 mm, 0.062 mm. Average particle size (Avg PS mm) was calculated by weighing the proportion of sediment sample that passed through each mesh size. Additionally, a 1 gram subsample of oven-dried sediments was analyzed for quantities and ratio of C and N (CNRatio) using an Elementar Vario Max CNS elemental analyzer (Analysensysteme GmbH, Hanau, Germany).

Data for each sample were compiled using Microsoft Excel and managed in a Microsoft Access relational database. Multivariate analyses were preformed using PRIMER version 7. For community analyses, macroinvertebrate data were arranged into matrix format, including factors for each sample (e.g., connectivity threshold, % organic matter, abiotic data), and an overall transformation was applied (4^{th} root) in order to balance the contributions of common and rare taxa to the analyses (Clarke et al. 2014;

Chapter 3 methodology). Similarities/dissimilarities between samples were then calculated from the transformed macroinvertebrate matrix using the Bray-Curtis coefficient (Bray and Curtis 1957). A dummy value (n=1) was added to the resemblance matrix to account for samples with small numbers of only one or two taxa, which can be highly variable in their dissimilarity (Clarke et al. 2014; Clarke et al. 2006). Main effect permutational analysis of variance (PERMANOVA) was used to test for differences in macroinvertebrate community along a gradient of hydrological connectivity, connection frequency at different time scales, and substrate types. Non-metric multidimensional scaling (nMDS) was applied to the macroinvertebrate resemblance data to visualize relationships between samples according to a variety of factors, including connectivity threshold, frequency of connection during a specified interval (3 month, 6 month, 1 year), and visual characterization of substrate type. A Similarity Percentages procedure (SIMPER) was used to identify typifying taxa for channels that were connected or disconnected at sampling for each substrate type. When a single taxon was typifying for more than one substrate type, it was color-coded for the substrate in which it had the highest contribution.

Connectivity metrics and field collected physio-chemical data (Table 4.2) were normalized for comparability, subjected to a resemblance matrix (Euclidian Distance) and ordinated using principal components analysis (PCA) (Clarke et al. 2014). To test for significance (Rho) between macroinvertebrate community data and the environmental/physical parameters which "best" explain them, the BEST BIO/ENV procedure was used to maximize the rank correlation between the two matrices (*see*

Chapter 3 for methodology). One way ANOVA was used to determine differences in particle size in channels connected/disconnected to/from main channel flow.

Table 4.2. Summary statistics for factors included in principal components analysis. Redundant/collinear factors removed from analysis noted by (*).

	Minimum	Maximum	Average	Standard deviation
Water velocity (m/s)	0	2.68	0.997273	0.73987
Surface Water Temp (C)*	14.6	27	21.82636	4.529142
Bottom Water Temp (C)	14.6	26.8	21.75159	4.697246
Measurement depth (m)*	0.13	21.34	6.04418	4.728850
Surface DO (mg/l)*	4.4	11.3	7.274773	1.895658
Bottom DO (mg/l)	3	9.9	6.754015	1.856039
Surface pH*	6.62	8.08	7.642727	0.28641
Bottom pH	7.07	8.03	7.605	0.24899
Turbidity (NTU)	16.8	570	153.0909	165.0212
CNRatio	0	385.0149	27.37476	42.47475
Avg PS mm	0.03	0.969961	0.342928	0.186284
% Organic Matter	0	15	1.640589	2.483268
Connectivity Threshold	130	160.5	145.5263	10.73496
1YrConnFreq	42.2	100	83.49091	18.76297
6MthConnFreq	53.8	100	90.92273	12.87808
3MthConnFreq	17.6	100	91.18182	18.96709

Results

Four sampling efforts over two years (spring 2014 & 2015, fall 2014 & 2015) resulted in the collection of 264 unique samples comprised of 6,998 individuals and 93 taxa (Appendix C). The majority of the macroinvertebrates were immature aquatic insects, with 1/3 of the taxonomic diversity and 3553 individuals represented by a single family of Diptera, the Chironomidae (non-biting midges). Other notable taxa included Ephemeroptera (10 families), other aquatic Diptera (5 families), Plecoptera (2 families), Trichoptera (2 families), Odonata (2 families), and Coleoptera (2 families). Crustaceans, mollusks, and annelids were also frequently collected.

The PERMANOVA resulted in a significant interaction between macroinvertebrate communities sampled along the hydrological connectivity gradient (Pseudo-F=5.5986, p<0.001) (Table 4.3). These interactions were visualized by examining the community in multidimensional space (nMDS; Figure 4.3). There was a clear separation (Pseudo F=26.951, p<0.001) of macroinvertebrate samples depending on whether the secondary channel was connected or disconnected at the time of sampling (Figure 4.4; Table 4.3), although no seasonal variation in macroinvertebrate community structure was detected when visualized in the ordination (Figure 4.5). Channels with flow-through connection at the time of sampling where characterized by obligate lotic taxa, such as net-spinning caddisflies (Trichoptera: Hydropsychidae), psammophilic Chironomidae (*Robackia, Chernovskiia, Lopescladius, Polypedilum, Cryptochironomus, Lipiniella,* etc.), Oligochaeta, and native amphipods (Gammaridae). Channels that were disconnected at the time of sampling were characterized by lentic or facultatively lotic taxa including Oligochaeta, *Chironomus, Cryptochironomus,* & *Coelotanypus* (Chironomidae), *Hexagenia* (Ephemeroptera: Ephemeridae), and non-native amphipod *Apocorophium lacustre*.

Table 4.3. PERMANOVA results for main effect PERMANOVA between macroinvertebrate communities and flow connectivity gradient.

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
Connectivity Threshold	15	1.67E+05	11152	5.5986	0.001	999
Res	248	4.94E+05	1991.9			
Total	263	6.61E+05				

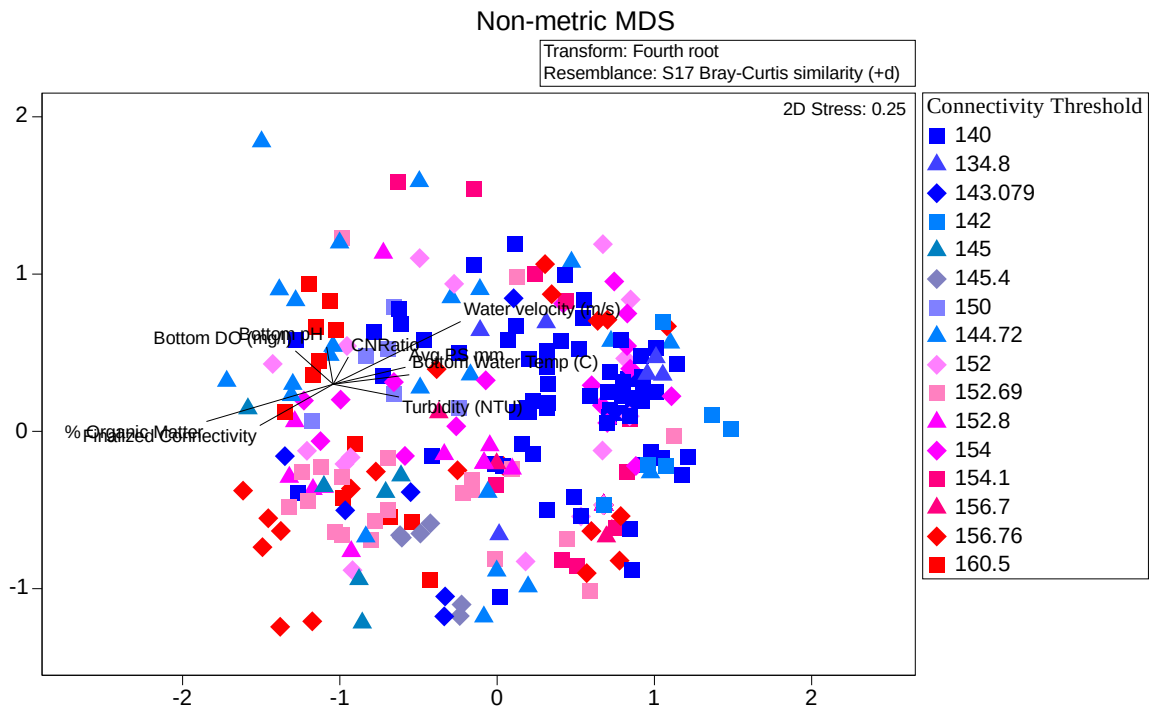

Figure 4.3. Non-metric multidimensional scaling of all macroinvertebrate samples (spring 2014-fall 2015) labeled by connectivity threshold (WSE in ft.) at which secondary channel becomes disconnected from the main channel. Physiochemical vectors are overlaid for context.

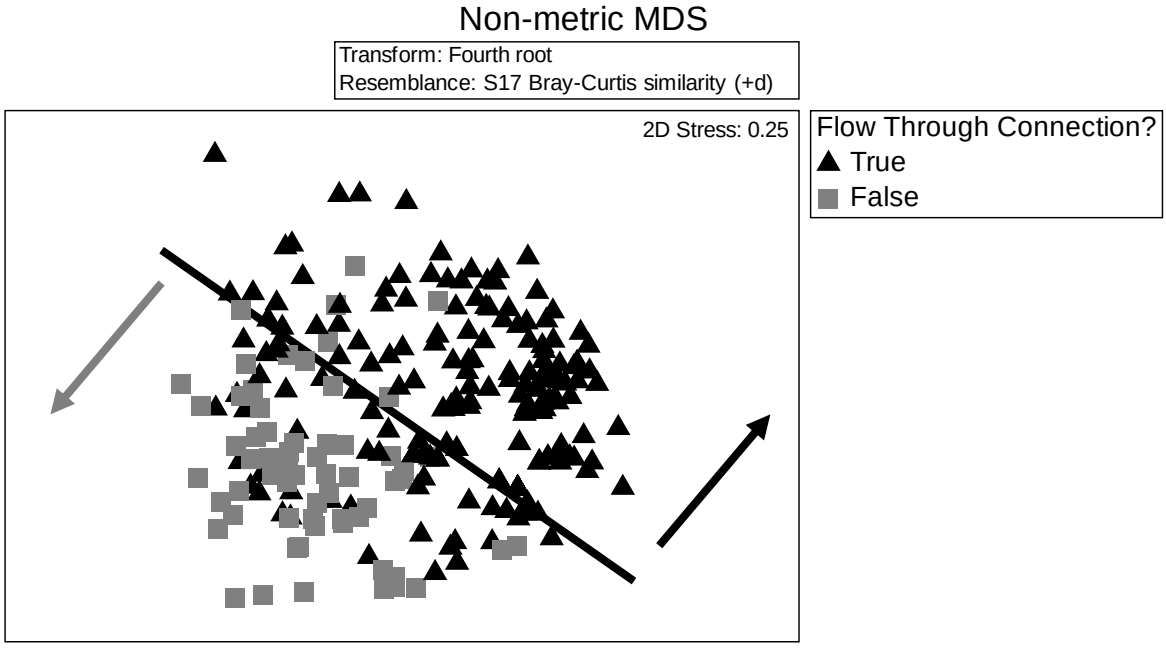

Figure 4.4. NMDS of macroinvertebrate community (spring 2014-fall 2015) labeled by presence/absence of flow in the secondary channel at the time of sampling.

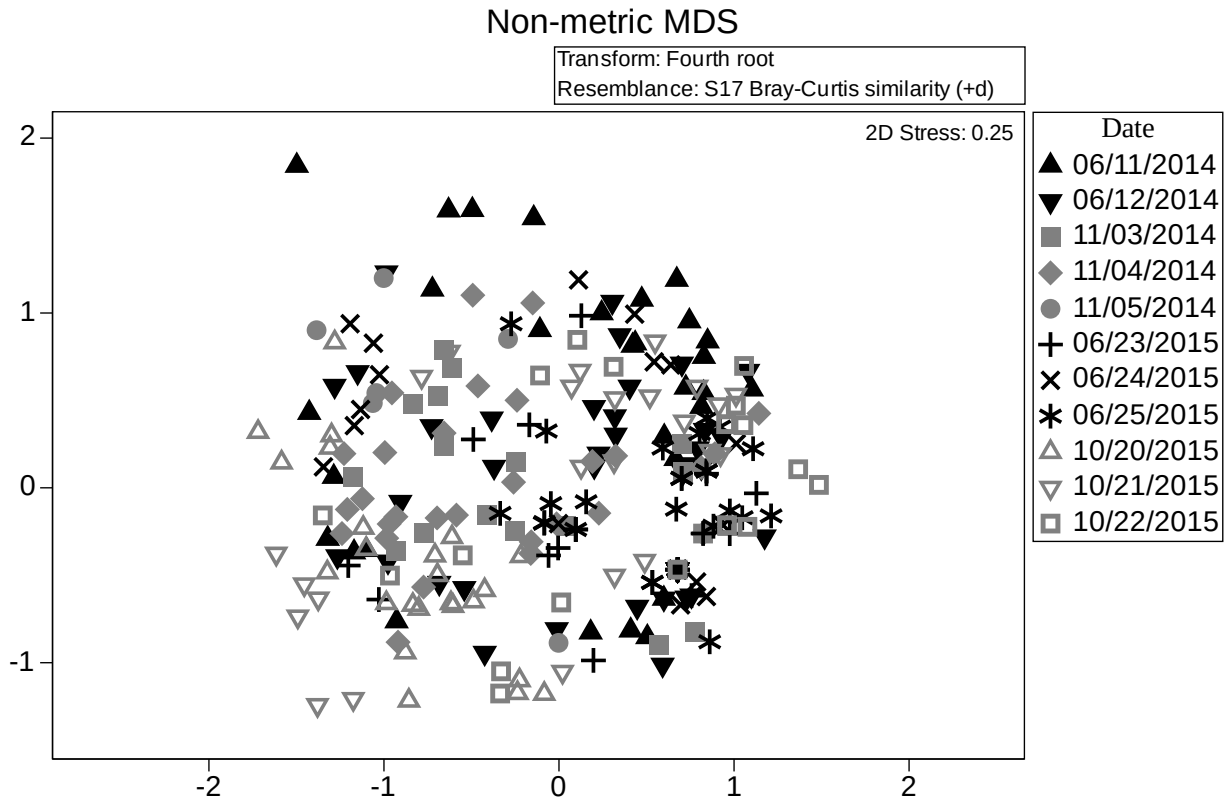

Figure 4.5. NMDS of macroinvertebrate community labeled by date collected (spring samples in black, fall samples in gray).

When controlling for flow connectivity during the time of sampling, there is a significant effect of legacy flow at all three time scales. If legacy flow had no effect, then Spring 2014 and 2015 samples, which were all connected at time of sampling, should be indistinguishable. However, there was a significant effect of legacy flow on community structure (Figure 4.6, Table 4.4).

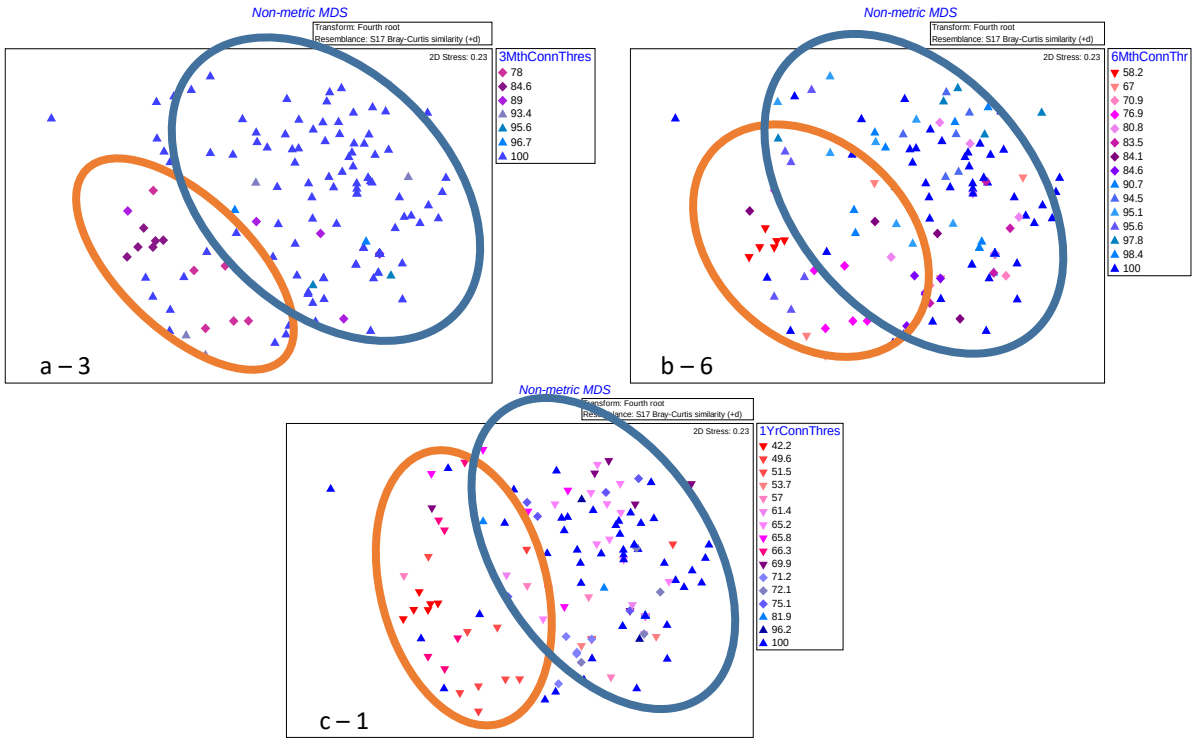

Figure 4.6. Spring 2014 & 2015 macroinvertebrate samples (all sites connected to the main channel at time of sampling) labeled by frequency of connection during (a) three months, (b) six months, and (c) one year prior to sampling.

Table 4.4. Pseudo-F and significance levels of main effect PERMANOVA of Spring 2014 & Spring 2015.

Source	**Pseudo-F**	**(significance)**
3 Month Connection Frequency	4.2337	(0.001)
6 Month Connection Frequency	4.5462	(0.001)
1 Year Connection Frequency	4.5486	(0.001)

To visualize how sites related to each other based on physio-chemical parameters, abiotic data for all sites, including water and sediment parameters, connectivity thresholds, and connection frequencies were first analyzed for collinearity using draftsman plots to check for and remove redundant variables (see Table 4.2). These data were normalized and a resemblance matrix (Euclidean distance) was created, followed by

a Principal Components Analysis, which resulted in a clear seasonal separation along PC1 due to water quality parameters, along PC2 based on connectivity thresholds and frequencies, and along PC3 based on sediment particle size and organic matter content (Figure 4.7; Table 4.5). A cumulative total of 67.9% of the variation was captured by PC1-PC3 (Table 4.5). To test for a biotic response to these abiotic parameters, the BEST procedure was performed on the macroinvertebrate resemblance matrix and the abiotic resemblance matrix to identify which abiotic parameters best explained patterns in macroinvertebrate community structure. This procedure resulted in statistically significant ($Rho=0.307$, $p<0.001$) interactions between macroinvertebrate community structure and average sediment particle size, water velocity, % organic matter in the sediment, and the frequency of connection during the year prior to sampling, which represent the strongest explanatory variables for observed community structure.

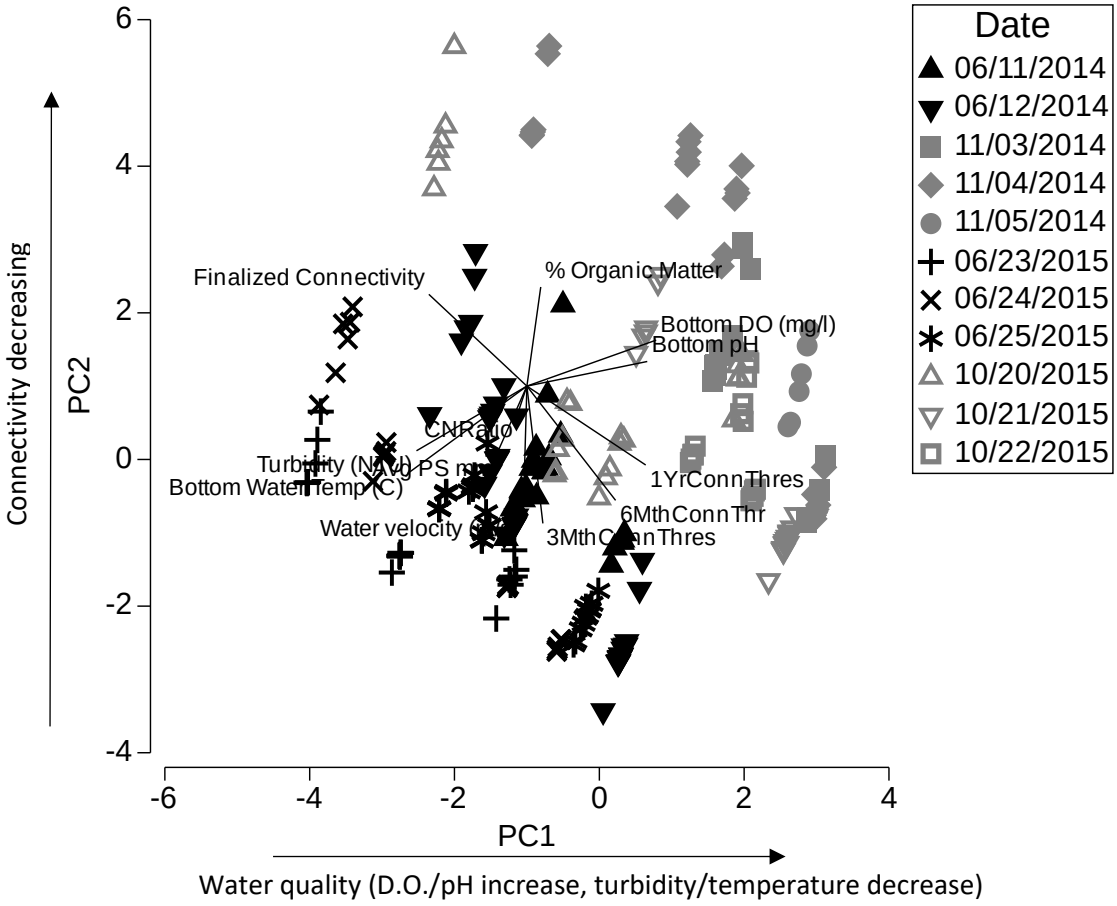

Figure 4.7. PCA ordination of site and habitat data, including connectivity metrics and physio-chemical properties of water and sediment, labeled by date (spring in black, fall in gray).

Table 4.5. Eigenvectors (coefficients in the linear combinations of variables making up PC's) of PC1-PC3 (67.9% variance accounted for).

Variable	PC1	PC2	PC3
Water velocity (m/s)	-0.012	**-0.422**	0.031
Bottom Water Temp (C)	**-0.396**	**-0.287**	-0.078
Bottom DO (mg/l)	**0.429**	0.151	**0.304**
Bottom pH	**0.399**	0.081	**0.317**
Turbidity (NTU)	**-0.367**	-0.212	-0.044
CNRatio	-0.032	-0.095	0.15
Avg PS mm	-0.1	-0.224	**0.645**
% Organic Matter	0.046	**0.325**	**-0.477**
Finalized Connectivity	**-0.326**	**0.301**	0.195
1YrConnFreq	**0.394**	**-0.259**	-0.237
6MthConnFreq	**0.295**	**-0.375**	-0.172
3MthConnFreq	0.053	**-0.45**	-0.087
% Variation	29.9	28.2	9.8

To further investigate the associations between particle size and community structure, the macroinvertebrate nMDS plot was labeled by sediment type. Clear differences in community composition across sediment types became evident (Figure 4.8a). A SIMPER analysis was used to identify typifying taxa for each sediment type. The most heavily contributing taxa were used to create a bubble plot overlay for visualization of taxonomic contribution to community type (Figure 4.8b). A PERMANOVA resulted in statistically significant differences in macroinvertebrate communities across primary substrate type (9.5808, $p<0.001$). Increased particle size is associated with increased water velocity and secondary channels with flow connectivity had coarser substrates (avg. 0.378 mm) that were significantly larger than disconnected channels (avg. 0.284 mm) (F=14.277; $p<0.001$).

For visualization of the legacy effect of flow connectivity on macroinvertebrate community makeup, a split bubble plot overlay was created for the nMDS labeled by flow connection frequency during the year prior to sampling (Figure 4.9). To visualize a

potential legacy effect of loss of flow connectivity on macroinvertebrate community makeup, particularly lotic obligate taxa, including riverine Chironomidae, Ephemeroptera, Trichoptera, and Plecoptera were selected for the split bubble overlay (Figure 4.9b). These taxa were selected due to their presumed sensitivity to loss of flow and this plot corresponds to the nMDS ordination of the macroinvertebrate community matrix labeled by flow frequency during the year prior to sampling, including all samples from all four sampling events (Figure 4.9a).

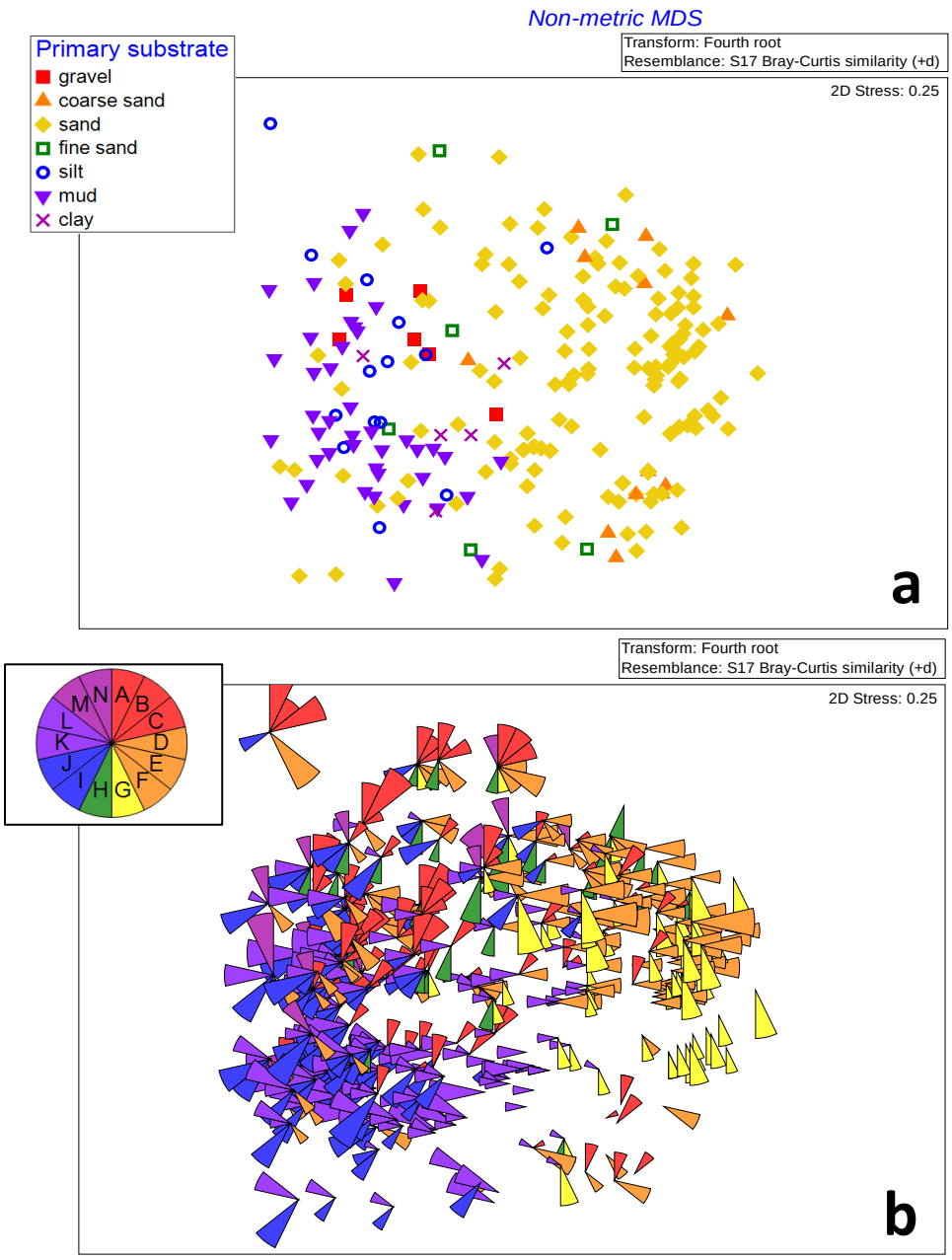

Figure 4.8. NMDS ordinations of macroinvertebrate community (a) labeled by primary substrate and (b) with split-bubble overlay including typifying taxa for each substrate type (SIMPER analysis). Slices from bubbles can be interpreted based on the color and direction of the slice for taxa (A-N). Red = gravel (A: *Gammaridae*; B: *Apocorophium*; C: *Potamyia*), orange = coarse sand (D: *Robackia*; E: *Lipiniella*; F: *Polypedilum*), yellow = sand (G: *Chernovskiia*), green = fine sand (H: *Corbicula*), blue = silt (I: *Hexagenia*; J: *Cryptochironomus*), indigo = mud (K: Oligochaeta; L: *Chironomus*), and violet = clay (M: *Tortopsis*; N: *Pentagenia*).

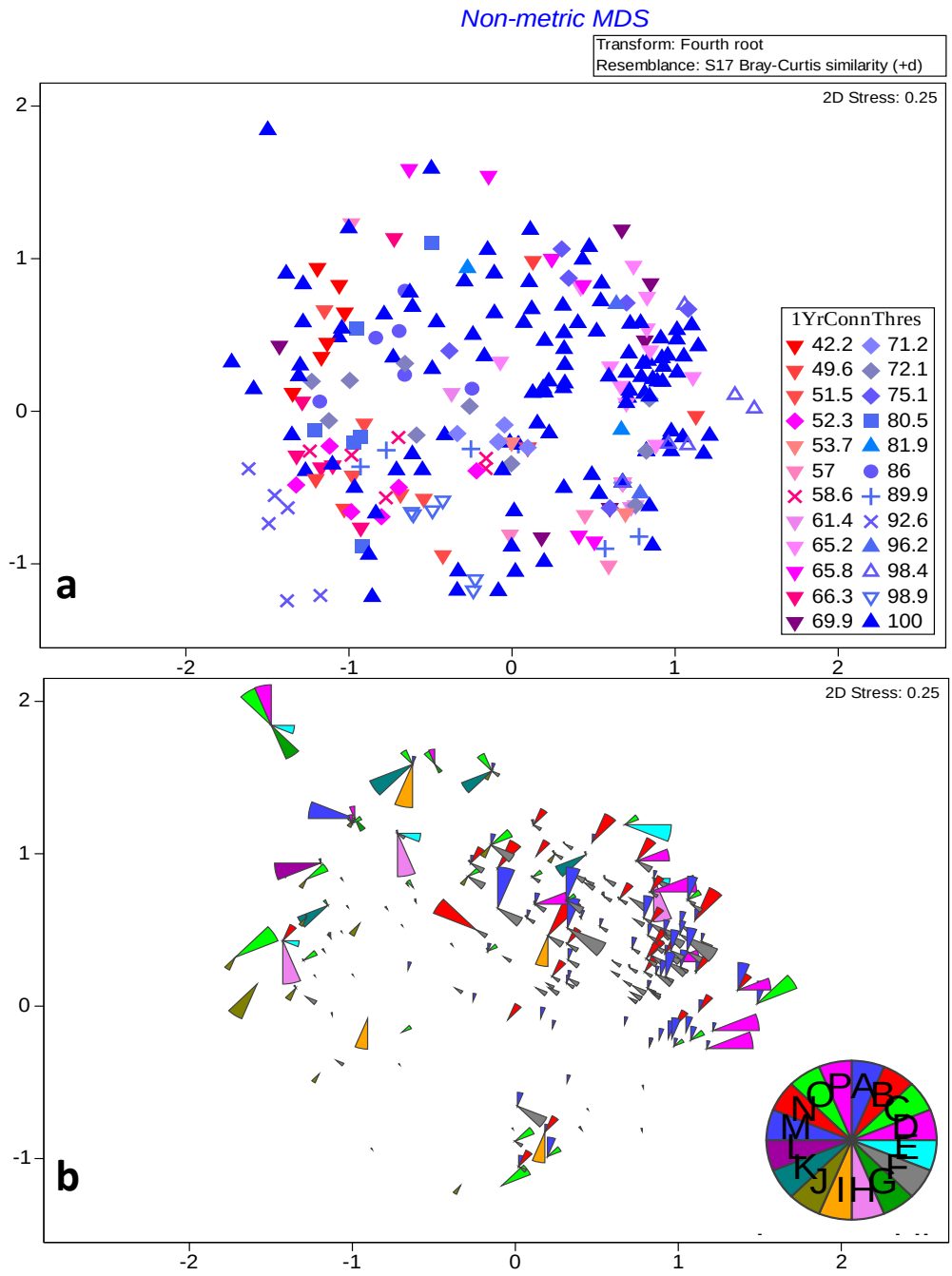

Figure 4.9. NMDS of macroinvertebrate community (all samples) labeled by 1 year connection frequency (a), and the same NMDS with a bubble overlay including lotic EPT and chironomid taxa (b) (A – *Chernovskiia*, B – *Lopescladius*. C – *Paratendipes*, D- *Rheosmittia*, E- *Saetheria*, F- *Robackia*, G – *Simulium*, H – *Neoephemera*, I – *Pseudiron*, J – *Pentagenia*, K – *Raptoheptagenia*, L – *Spinadis*, M – *Perlesta*, N – Perlodidae, O – *Potamyia*, P – *Hydropsyche*).

Discussion

Secondary channels are one of the most common habitat types in large rivers worldwide, and their function as part of the river ecosystem is critical, given the extensive anthropogenic impact on large river systems. In the Lower Mississippi River, secondary channels retain more natural habitat features than main channel habitat and have the potential to serve as permanent refugia for a multitude of riverine organisms, including endangered species. The Pallid Sturgeon, Interior Least Tern, and Fat Pocketbook Mussel, have all been documented in LMR secondary channels (Killgore et al. 2014). However, secondary channel availability and benefit for these and other riverine species is likely controlled by their accessibility, environmental stability, and possession of trophic resources (Hynes 1970).

Many aquatic macroinvertebrates are classified by their presence in either lentic or lotic environments (Hynes 1970; Merritt et al. 2008), and as expected, there was a visible community shift in channels that were disconnected from main channel flow at the time of sampling when compared to channels that were connected at the time of sampling (Figure 4.4). Channels with flow through connectivity were characterized by obligate lotic taxa, whereas channels disconnected from main channel flow were characterized by lentic or generalist taxa. However, this trend only continues until channels are reconnected to main channel flow because many substrate dwelling lentic taxa are not adapted to maintaining station in high flows.

Some of the secondary channels evaluated in this study were disconnected from main channel flow almost 60% of the year, ranging from 42.2 – 100% yearly flow through connection dependent on river stage and flow connectivity thresholds.

Macroinvertebrate communities reflect this loss of flow, not only at the time of flow disconnection, but in some cases, for an entire year or more, indicating a resulting legacy effect. This is likely a result of timing of disconnection and reconnection of channels. Although we lack the sample frequency necessary for an empirical test, we hypothesize that when channels are disconnected and lotic communities are replaced with lentic communities, lentic communities are washed away upon reconnection, but as this typically happens in winter, the timing is not appropriate for recolonization by ovipositing adult aquatic insects. While there is opportunity for drifting macroinvertebrates to colonize these channels, as demonstrated by Koetsier and Bryan (1989) and Obi and Conner (1986), they would have to be present in the top of the water column in order to pass over dikes into connected secondary channels, and there is evidence that drift densities are lowest at the surface (Beckett and Kasul 1987). This could explain in part, the reduced occurrence of obligate lotic taxa in channels that have been disconnected for an extended amount of time (i.e., >10% of the time) throughout the year, even when channels were connected at the time of sampling (Figure 4.9). This is of particular concern because many of these taxa are EPT (Ephemeroptera, Plecoptera, Trichoptera) taxa, which are generally indicators of ecosystem health and good water quality (Flotemersch et al. 2006; Merritt et al. 2008). In addition, these are for the most part large-bodied macroinvertebrates, which are high-quality prey items for fishes, and have the capability of removing, assimilating, and transferring large quantities of nutrients from the river system (Armitage 1995; Covich et al. 1999; Cummins 1973; Cummins and Klug 1979; Freeman and Wallace 1984; Malmqvist 2002; Merritt et al. 2008; Nakano and Murakami 2001).

In the Mississippi River Basin's sediment-rich system, loss of flow results in fine sediment deposition. Sediment particle size was highly correlated with macroinvertebrate community composition, and substrate type is well known as a driver of community structure (Beckett et al. 1983b; Buss et al. 2004; Hynes 1970). Macroinvertebrates utilize different substrates in different ways to complete life history processes such as feeding, flow refugia, locomotion, and predator avoidance (Cummins and Lauff 1969; Merritt et al. 2008). With this information and further study into macroinvertebrate/substrate interactions, substrate type should be used in future planning for restoration targets and management of large river secondary channels (Jähnig and Lorenz 2008).

Efforts are currently underway to increase the flow frequency of LMR secondary channels by notching closure dikes to lower the flow connection threshold (LMRCC 2015). Establishing permanent flow is the first and most important step in restoration of lotic habitats for use by obligate riverine species. However, there is little understanding of the effects of varying notch widths and depths. More research is needed to understand the biotic response at multiple organismal levels in order to refine the elevation threshold to achieve desired goals. In addition, future efforts should be paired with creation and restoration of natural habitat features to increase habitat and structural heterogeneity, in order to maximize the secondary channel habitat niches available to riverine organisms. To achieve greatest macroinvertebrate diversity, future efforts should seek to increase the habitat heterogeneity of secondary channels. These efforts should focus on creating pilot channels to maintain permanent flow during low water, creating areas with variable depth profiles to create temporary lentic habitat for colonization by lentic species, and adding natural structure to channels to provide suitable habitats for clinging organisms. These

efforts will not only benefit macroinvertebrates, but will ensure that secondary channels are bioavailable to the widest variety of fishes, reptiles, amphibians, and birds.

Acknowledgements

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CHAPTER V:

NUTRIENT & WATER AND SEDIMENT CHEMISTRY DYNAMICS OF SECONDARY CHANNELS IN THE LOWER MISSISSIPPI RIVER

ABSTRACT

Connectivity is not only a driving factor for macroinvertebrate community dynamics, but also a primary driver of nutrient fluxes and physiochemical dynamics within large rivers. Secondary channels, a common habitat feature in the Lower Mississippi and other large rivers, are offset from the main channel, and due to modifications of the system, experience disconnection from main channel flow. The primary objective of this study was to analyze the effects of connectivity of secondary channels on the physiochemical properties of water and sediments. Secondary channels, both connected and disconnected, were compared to the fully connected main channel at high river stages (spring) and low river stages (fall). These results indicate that secondary channels differ from the main channel in several ways. In spring and fall, connected secondary channels had lower mean water velocities and higher percent organic matter in the substrates than the main channel. In addition, physiochemical measurements of water and sediment characteristics change with disconnection. At low river stages, disconnected secondary channels were transformed into temporary backwaters, with no flow, increased water temperatures, decreased dissolved nutrient concentrations, and increased organic load in the sediments. As a consequence of the natural flow regime, these fluxes are temporary, only lasting until the next reconnection event.

Introduction

Connectivity influences the biotic and abiotic structure of habitats (Cloern 2007; Hein et al. 2003, 2004; Pongruktham and Ochs 2014; Tockner et al. 1999, 2000). In fluvial systems, hydrological connectivity, the movement of water, is the primary driver of nutrient transfer into and out of aquatic habitats. In large-river floodplain systems, this occurs in a multidirectional manner, occurring laterally (across the floodplain), longitudinally (downstream), and vertically (throughout the water column) (Amoros and Bornette 2002; Amoros et al. 1987; Ward 1989; Ward et al. 1999). Nutrient and physiochemical relationships with connectivity in large river floodplains have been documented and there are strong relationships between inundation frequencies, primary production, and nutrient loading (Heiler et al. 1995; Pongruktham and Ochs 2014).

In a highly turbid river, such as the Mississippi, any reduction of current velocity will have broad impacts on the aquatic environment. Channel habitats of the Mississippi River are typically light-limited (Ochs et al. 2013). Because of human modification of the Lower Mississippi River through the instream placement of dikes, secondary channels do not function as permanent riverine channels. Instead, they become isolated slackwater or backwater habitats on a seasonal basis, depending on their connection threshold (elevation of disconnection) and the river stage.

Also of concern is the fact that Lower Mississippi River waters carry enough nutrient pollutants to devastate its delta and mouth each year through Gulf hypoxia. Last year's dead zone set a record, measuring >22,000 km^2 (LUMCON 2017), raising questions about nutrient dynamics in the Lower Mississippi River and the role of secondary channels in nutrient processing, such as: Do disconnected secondary channels

sink significant amounts of nutrients? *and* Are secondary channels appropriate surrogates for floodplain habitat, most of which was lost with main-line levee construction? This study cannot answer those larger questions, but can address others, such as: Do secondary channels and the main channel differ in their physiochemical properties? Is there an effect of connectivity on the concentrations of nutrients in the water column and in sediments? To answer these questions, secondary channels varying in connectivity to the main channel of the LMR were sampled in high water and low water over a two year period.

Methods

Sample collection

Within a 150-km reach of the Lower Mississippi River, fourteen secondary channels (Appendix A) variable in their frequency of connection to the main channel, as well as the main channel, were sampled for analysis of water chemistry and sediment chemistry during high water and low water over two years. At the mid-point of each site, a YSI Pro DSS was used to measure the following measurements at the water surface and bottom: water temperature (°C), dissolved oxygen, pH, conductivity (µS/cm), oxidation-reduction potential, and turbidity (NTU). Surface water velocity (cm/s) was measured using a Marsh-McBirney, Inc. Flow Mate Model 2000. Triplicate water samples were taken at approximately 0.5-m below the surface by hand, and 0.5-m above the substrate by pumping water from within 1 m of the bottom using a Cole-Palmer Model 7570-10 peristaltic pump. Water was collected in sterile Fisherbrand sample bags, labeled, placed on ice, and filtered within 12 hours of collection. In the lab, water was vacuum-filtered

through 45-mm Whatman GF/F filters (100 mL) and 25-mm Whatman GF/F filters (25 mL). Filters were wrapped in aluminum foil and filtrate was stored in sterile sample bags, and frozen at -60°C upon returning to the laboratory. Additionally, six 50-mL sediment samples were taken from each channel using a benthic sled (see Chapter 2 for methodology). Sediment samples were placed on ice and frozen at -60°C upon return to the laboratory.

Sample processing

Filtrate from water samples were subsampled into 100-mL aliquots, filtered through 0.45 µm cellulose membrane filters, preserved with 98% H_2SO_4 (1µL/1mL), and analyzed for dissolved nutrients, including: NH_4^+-N (mg/L), PO_4^{3-}-P (mg/L), NO_X-N (mg/L), NO_2^--N (mg/L), and NO_3^--N (mg/L), using a Lachat QuikChem 8500 Series 2 with an ASX-260 Series autosampler (Hach, Loveland, CO). These measurements were made at the Water Quality Laboratory of the Department of Wildlife, Fisheries, and Aquaculture at Mississippi State University, Starkville, MS, according to methods outlined by Eaton et al. (1998). Particulate matter isolated from surface and bottom water samples was analyzed from two glass fiber filters (Whatman GF/F). Filtered seston collected on the 47-mm filters was analyzed for chlorophyll *a* (Chl *a*) and pheophytin *a* (Pheo *a*), which were used to estimate living and dead algal biomass, respectively, according to the methods of Wetzel and Likens (2000). Filtered seston from the 25-mm filters was analyzed for measurements of stable isotopes of C and N. Unfortunately, after analysis of five random test samples, it was determined that there was not enough C or N

to be traceable at an acceptable level of confidence. Sediment samples were analyzed for percent organic matter and C:N, as described in Chapter 4. Additionally, 10 test samples of sediments were analyzed for stable isotope ratios of C:N, but concentrations were not high enough for detection, therefore no more samples were analyzed. Finally, 14 test sediment samples composed of sand were analyzed for pigment concentrations using methodology outlined in Zimba et al. (2016), however there were no traceable pigments present in any of the sediment samples tested, thus no further samples were analyzed.

Connectivity

Connectivity was calculated using the methodology outlined in Chapter 4. For these analyses, connectivity groups were defined as (1) Control/fully connected = Main Channel; (2) Connected Secondary Channels; (3) Disconnected Secondary Channels.

Data analysis

Using PRIMER version 7, water and sediment metrics were normalised and resemblance matrices (Euclidean distance) were constructed. Metric multidimensional scaling was used to visualize seasonal influences on environmental resemblance structure of water and sediments. Water and sediment data were analyzed separately due to differences in collection technique and sample numbers. Triplicate surface and bottom samples were treated as individual replicates within each site. Highly correlated (>75% Pearson correlation) variables were overlaid on ordinations to visualize contributions to observed patterns. Using SAS version 9.4, multivariate analysis of variance (MANOVA) was used to test for overall effects of season and connectivity, and their interaction, on

sediment and water physical and chemical parameters and the Wilks' likelihood ratio test statistic (Λ) was chosen. This test produces an F-statistic and associated level of significance. Generalized linear mixed models (GLIMMIX procedure) were then used to test for individual differences in physiochemical parameters by season and connectivity, and their interaction. These models were chosen for the inclusion of both fixed (season, connectivity) and random effects (site, year), and an unstructured covariance structure was used to allow for the non-independence between samples at a site. Percent N in sediments was removed from the model because of the high percentage of near zero values. Highly skewed variables, including: % C, C:N, % organic matter, NH_4^+-N, PO_4^{3-} P, and turbidity were $\log_{10}$ transformed. Because the experimental design was unbalanced (i.e., not all sites were sampled at every outing), denominator degrees of freedom were calculated using the Kenward-Roger approximation (Kenward and Roger 1997). Least squares means were estimated on fixed and random effects and mean plots with both fixed effects (connectivity and season) were produced. Tukey HSD adjusted means were used to adjust for multiple simultaneous comparisons (Gotelli and Ellison 2004).

Results and Discussion

Water

Metric multidimensional scaling (mMDS) resulted in clear differences in water physiochemical properties by sampling date and connectivity (Figures 5.1, 5.2). Spring samples (2014 & 2015) grouped together along MDS 1, indicating similar conditions. Fall samples separated along MDS 1, but there was also a separation along MDS 2 by year (Figure 5.1). Dissolved oxygen, pH, phosphate, nitrate, turbidity, and temperature

were highly correlated with the metric multidimensional scaling axes. Spring samples were associated with higher water temperatures, higher levels of turbidity, and increased concentrations of phosphate and nitrate, all of which are expected in June when river stages are typically high. Conversely, higher dissolved oxygen concentrations and increased pH were observed in fall samples, likely a result of cooler water temperatures and a possible increase in biological activity in disconnected secondary channels. Metric multidimensional scaling resulted in differences in nutrients across the connectivity gradient (Figure 5.2). Connected sites, including the main channel and connected secondary channels were correlated with higher concentrations of phosphate and nitrate than disconnected secondary channels.

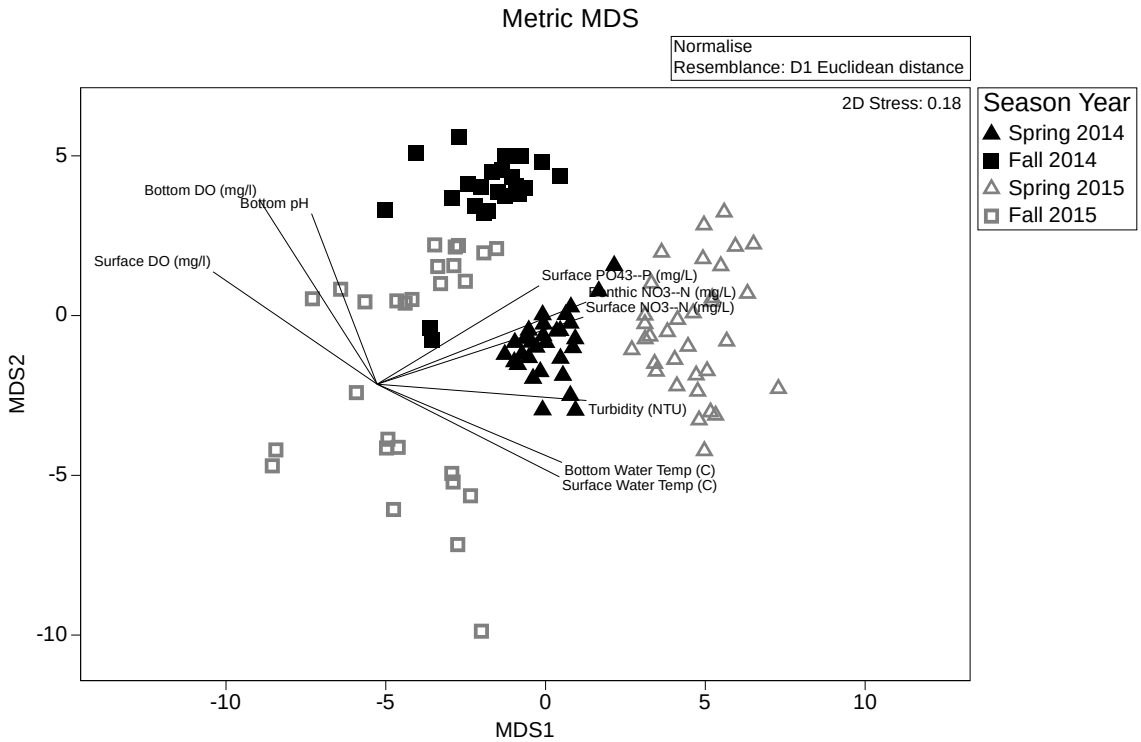

Figure 5.1. Metric multidimensional scaling (mMDS) of water physiochemical metrics labeled by season and year. Vectors represent variables highly correlated (>0.75) with MDS axes 1 & 2.

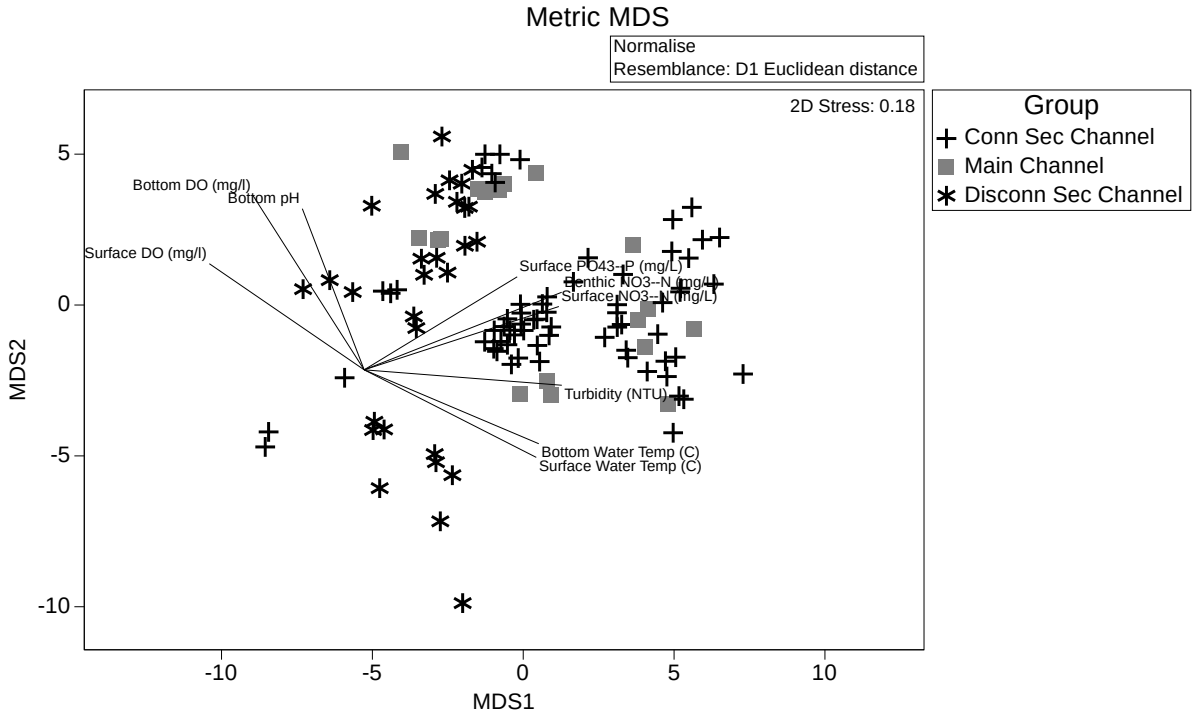

Figure 5.2. Metric multidimensional scaling (mMDS) of water physiochemical metrics labeled by connectivity grouping. Vectors represent variables highly correlated (>0.75) with MDS axes 1 & 2.

Multivariate analysis of variance (MANOVA) resulted in significant differences in overall water physiochemical metrics by season (Wilks' Λ=0.116; $p<0.0001$), connectivity type (Wilks' Λ=0.286; $p<0.0001$), and the interaction of both effects (Wilks' Λ=0.877; $p=0.0094$). The GLIMMIX procedure resulted in higher mean water velocities in spring samples compared to fall, which was expected due to the natural hydrograph (spring pulse) of the Lower Mississippi River. Higher mean water velocities were observed in the main channel versus connected and disconnected secondary channels (Figure 5.3). This reduction in current velocity is likely a result of secondary channels being offset from the main channel combined with the effects of structural impoundments at the upstream end, and highlights their importance for flow refugia for riverine

organisms. Mean turbidity measurements (NTU) followed water velocity, with significantly higher turbidities in spring than in fall, and with connected secondary channels having reduced mean turbidity (Figure 5.4). The Mississippi River is a highly turbid system, with a high suspended sediment load at high velocities, so this pattern was expected. Disconnected secondary channels however, had a slightly increased mean turbidity value during the fall sampling period than connected secondary channels (Table 5.1), which was probably a result of increased algal production in these channels, as light limitation decreased with precipitating sediments.

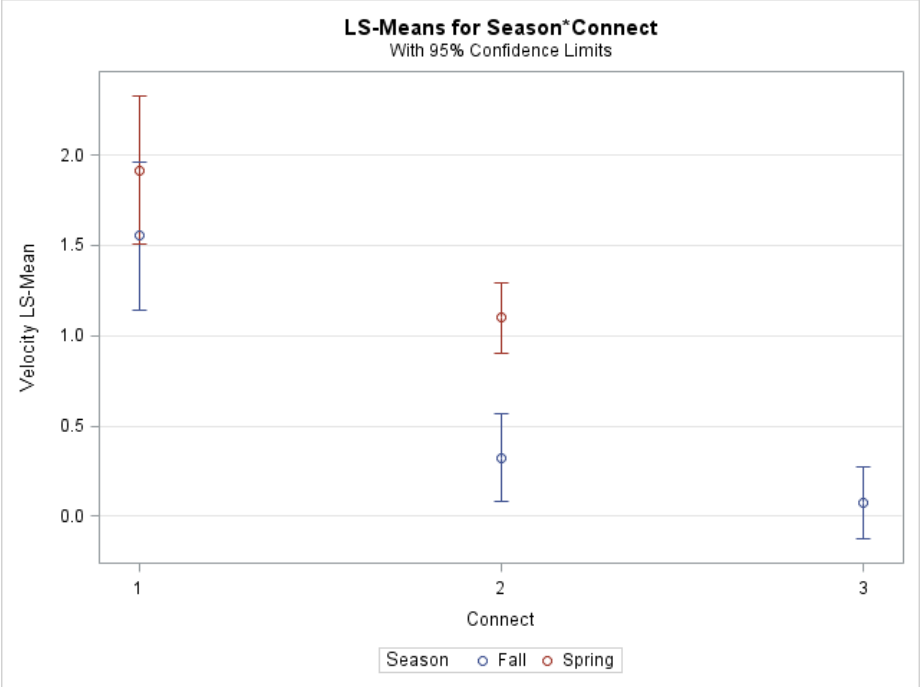

Figure 5.3. Means plot (LS-Means) of water velocity (m/s) by season and at different connectivity types (1=fully connected control/main channel, 2=connected secondary channels, 3=disconnected secondary channels).

Table 5.1. LS-Means (95% confidence interval) of water physiochemical metrics for each connectivity group and season. Means of log-transformed variables were back transformed and letters to the right of the numbers represent statistical differences between groups in that row based on Tukey HSD tests.

	Season	1	2	3
		Main Channel	Connected Sec. Chann.	Disconnected Sec. Chann.
Velocity (m/s)	Spring	1.92 (1.53, 2.30) **a**	1.10 (0.91, 1.28) **b**	-
	Fall	1.55 (1.93, 1.17) **a**	0.33 (0.09, 0.56) **b**	0.07 (-0.18, 0.19) **c**
Temp.(°C)	Spring	26.19 (24.73, 27.64)	26.46 (25.77, 27.15)	-
	Fall	16.27 (14.81, 17.72) **a**	15.93 (14.93, 16.92) **a**	17.25 (16.54, 17.96) **b**
D.O. (mg/L)	Spring	5.57 (4.00, 7.13)	5.08 (4.34, 5.82)	-
	Fall	9.28 (7.18, 10.85) **a**	9.35 (8.35, 10.35) **a**	8.16 (7.40, 8.91) **b**
pH	Spring	7.52 (7.28, 7.77)	7.39 (7.27, 7.50)	-
	Fall	7.92 (7.68, 8.17) **a**	7.95 (7.78, 8.11) **a**	7.68 (7.56, 7.80) **b**
Turbidity (NTU)	Spring	247.4 (246.23, 262.34)	205.16 (204.08, 217.16)	-
	Fall	41.85 (14.94, 56.79) **a**	21.44 (20.27, 36.34) **b**	25.07 (23.98, 37.41) **b**
Ammonium-N	Spring	0.04 (0.02, 0.11)	0.04 (0.01, 0.09)	-
	Fall	0.02 (0.01, .06)	0.04 (0.02, 0.11)	0.03 (0.01, 0.08)
Phosphate	Spring	0.08 (0.03, 0.22)	0.07 (0.02, 0.15)	-
	Fall	0.08 (0.04, 0.22)	0.06 (0.02, 0.15)	0.04 (0.01, 0.09)
Nitrate-N	Spring	1.87 (1.46, 2.29)	1.618 (1.41, 1.82)	-
	Fall	1.40 (0.98, 1.81)	1.30 (0.94, 1.65)	1.01 (0.80, 1.22)
Chlorophyll-*a*	Spring	10.22 (5.51, 14.94)	7.27 (4.95, 9.59)	-
	Fall	3.38 (0, 8.18)	6.845 (2.02, 11.67)	5.97 (3.35, 8.59)
Pheophytin-*a*	Spring	0 (0, 5.85)	4.71 (1.39, 8.02)	-
	Fall	7.59 (0.81, 14.37)	6.95 (0.36, 13.53)	11.71 (8.10, 15.32)

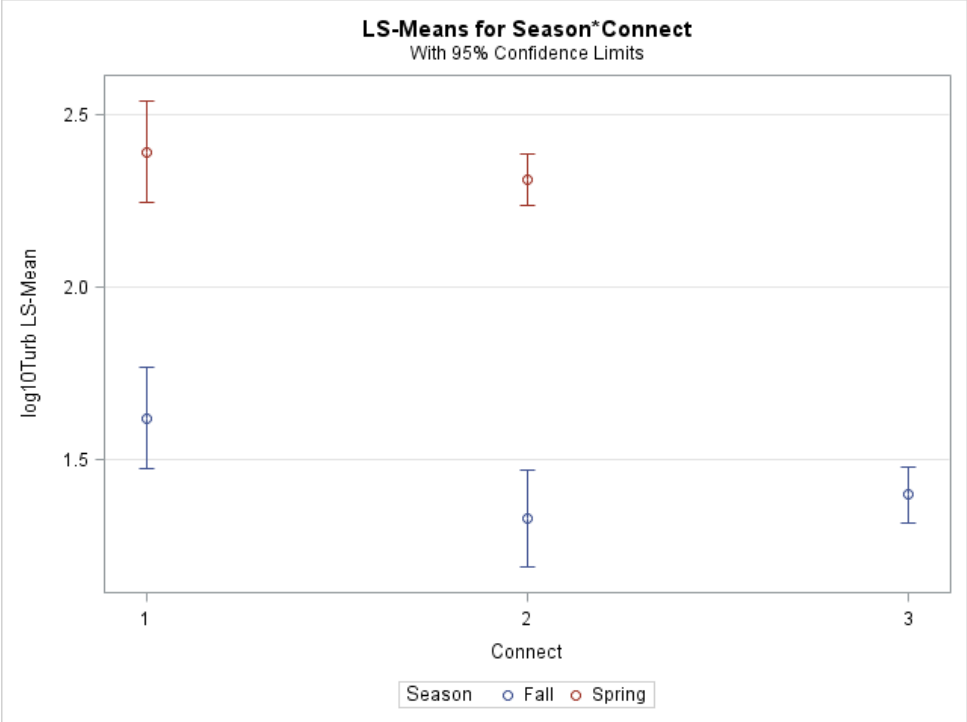

Figure 5.4. Means plot (LS-Means) of turbidity (NTU) by season and at different connectivity types (1=fully connected control/main channel, 2=connected secondary channels, 3=disconnected secondary channels).

Mean water temperature values were higher in spring samples compared to fall samples (Figure 5.5). Mean water temperatures did not differ significantly across connectivity types, except in the fall, disconnected secondary channels were slightly warmer on average than connected sites, which is expected based on prior observations (Table 5.1) (Pongruktham 2012). Conversely, mean dissolved oxygen (mg/L) values were higher in fall than in spring, which at full O_2 saturation is expected in cooler water (Figure 5.6). Disconnected secondary channels had lower mean dissolved oxygen concentrations than connected secondary channels (Table 5.1). Likewise, there were significant differences in mean pH levels by season and between connected and disconnected secondary channels (Figure 5.7). Higher mean pH values were recorded in

fall samples than in spring, and lower mean pH values were observed in disconnected secondary channels compared to connected secondary channels (Table 5.1).

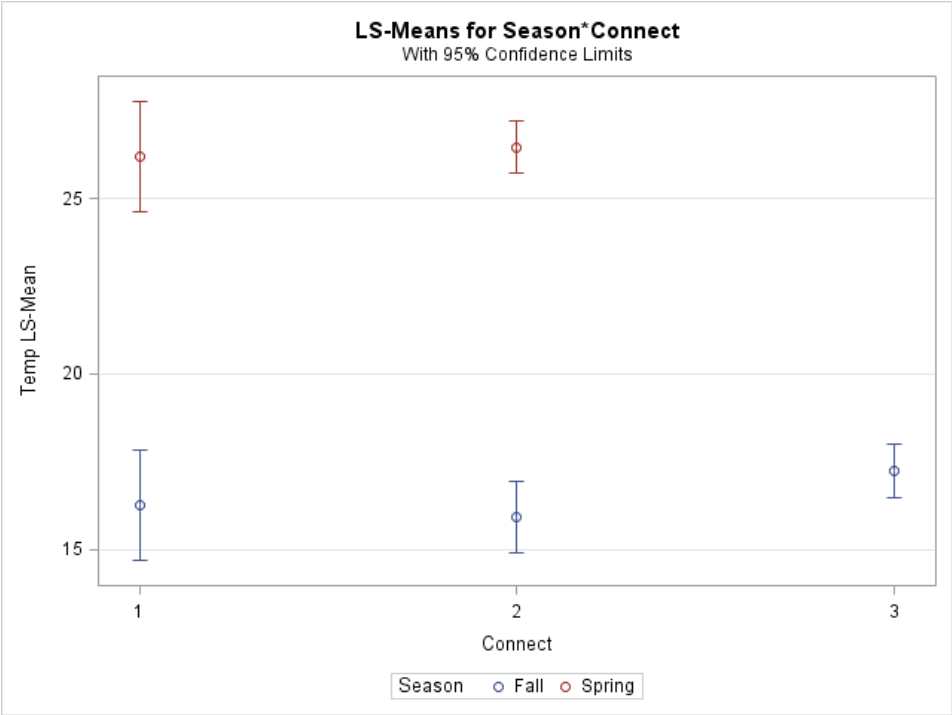

Figure 5.5. Means plot (LS-Means) of water temperature (°C) by season and at different connectivity types (1=fully connected control/main channel, 2=connected secondary channels, 3=disconnected secondary channels).

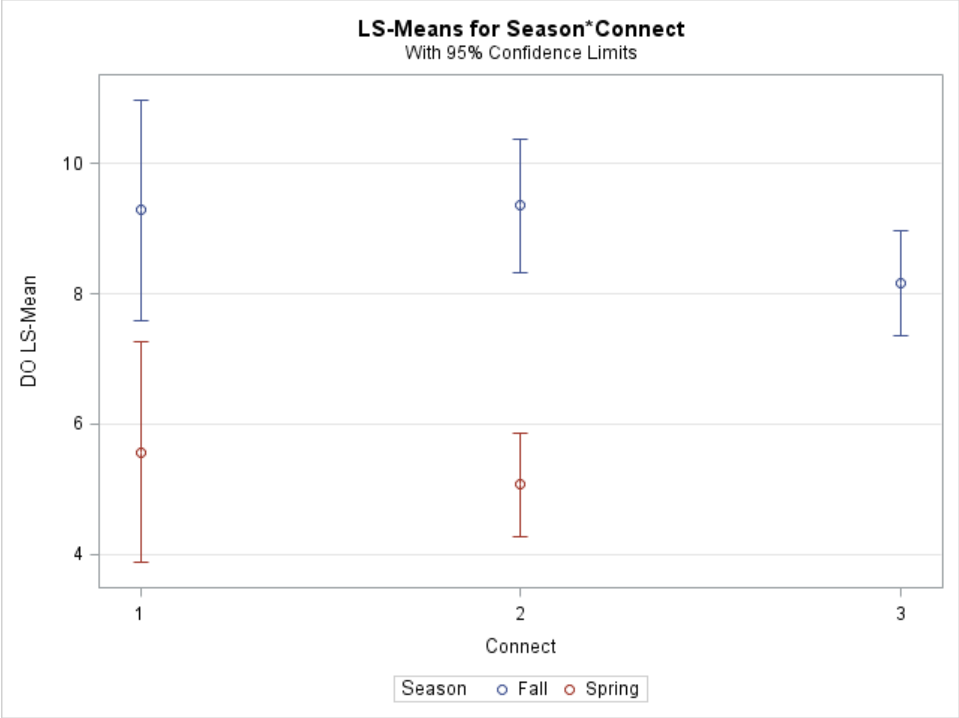

Figure 5.6. Means plot (LS-Means) of dissolved oxygen concentrations (mg/L) by season and at different connectivity types (1=fully connected control/main channel, 2=connected secondary channels, 3=disconnected secondary channels).

Variability was high in measurements of both dissolved ammonium-nitrogen (NH_4^+-N) and phosphate (PO_4^{3-}-P) and no significant differences were found between seasons or connectivity types (Figures 5.8-5.9; Table 5.1). Mean phosphate levels, however, seemed to decline with decreased connectivity, which could be indicative of uptake within disconnected sites. Mean nitrate-nitrogen (NO_3^--N) was higher in spring than fall ($F=5.19$; $p=0.04$) and declined with decreased connectivity, although not significantly ($F=2.25$; $p=0.14$) (Figure 5.10; Table 5.1).

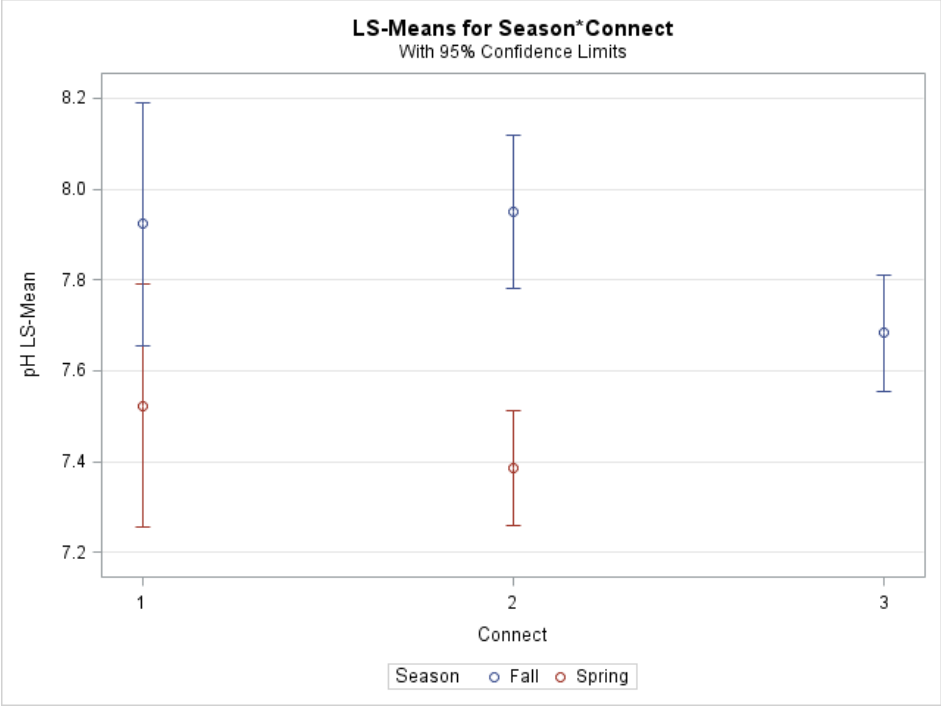

Figure 5.7. Means plot (LS-Means) of pH levels by season and at different connectivity types (1=fully connected control/main channel, 2=connected secondary channels, 3=disconnected secondary channels).

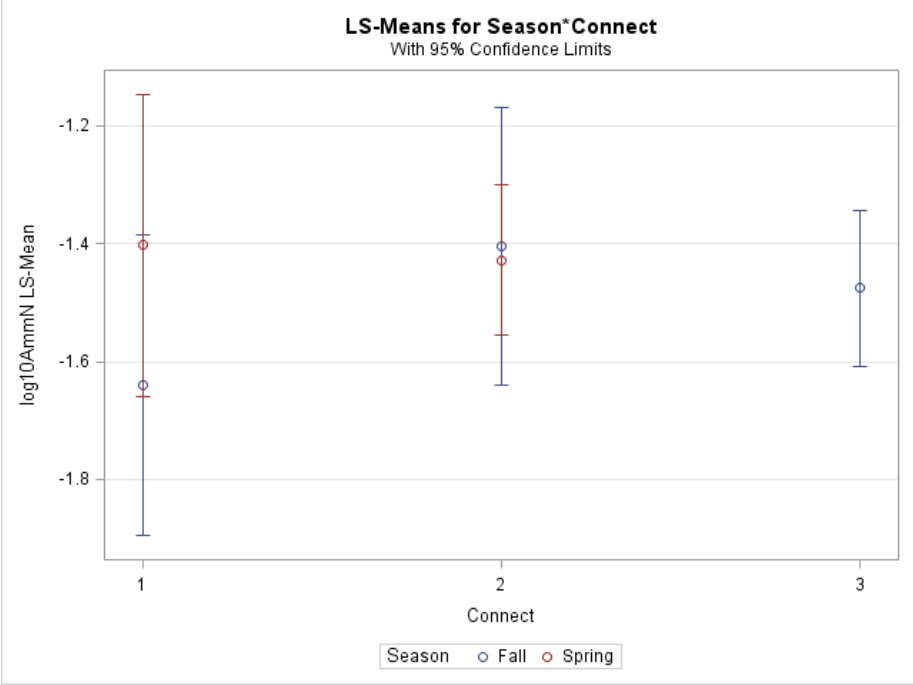

Figure 5.8. Means plot (LS-Means) of dissolved ammonium-nitrogen (NH_4^+-N) by season and at different connectivity types (1=fully connected control/main channel, 2=connected secondary channels, 3=disconnected secondary channels).

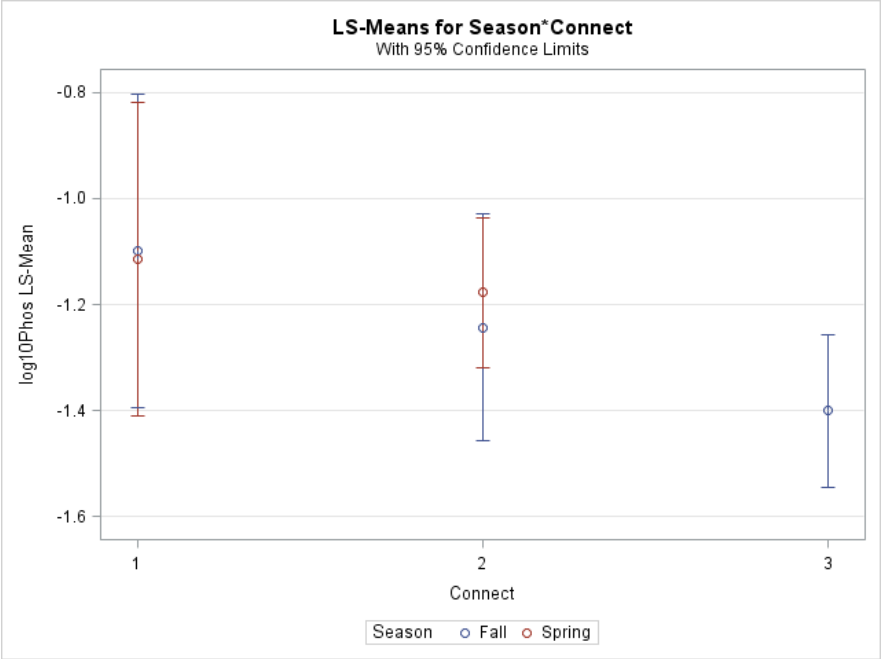

Figure 5.9. Means plot (LS-Means) of dissolved phosphate (PO_4^{3-}) by season and at different connectivity types (1=fully connected control/main channel, 2=connected secondary channels, 3=disconnected secondary channels).

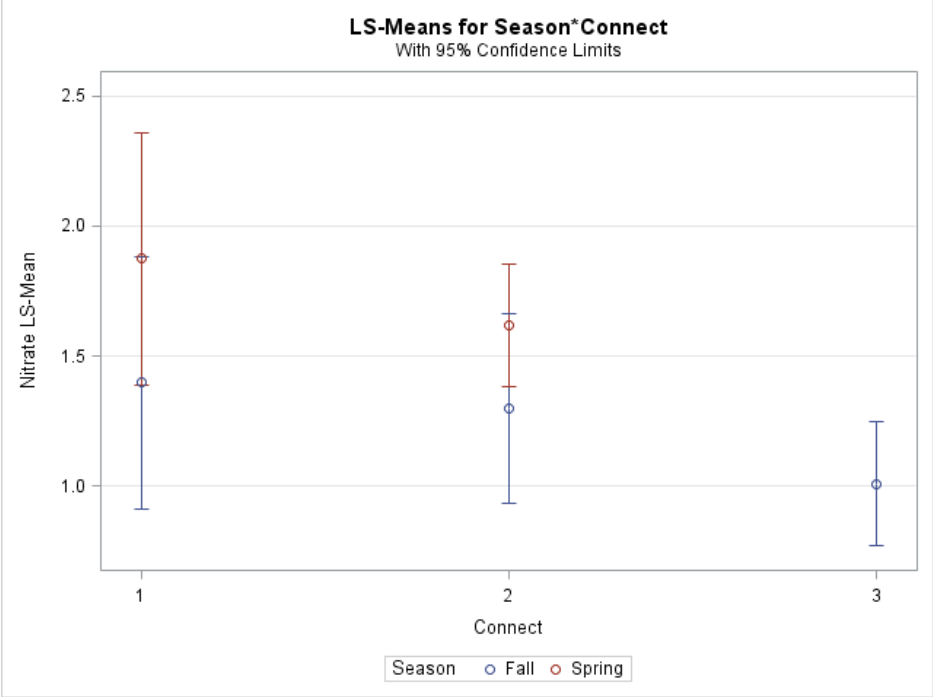

Figure 5.10. Means plot (LS-Means) of dissolved nitrate-nitrogen (NO_3^--N) by season and at different connectivity types (1=fully connected control/main channel, 2=connected secondary channels, 3=disconnected secondary channels).

Differences in chlorophyll-*a* concentrations, a surrogate for living algal biomass, were not significant over season or year (Figure 5.11; Table 5.1). These values were generally low, but comparable to other studies of this system (Pongruktham and Ochs 2014). Algal production can spike in disconnected secondary channels, but the increase is short-lived (Pongruktham and Ochs 2014), and was likely missed in channels sampled in this study. In addition, there was relatively high variability in these readings, limiting the interpretation of these data. Pheophytin-*a*, a surrogate for dead algal biomass, was on average higher in fall than spring (F=3.15; p=0.0897) (Figure 5.12; Table 5.1), and could be indicative of algal production prior to sampling. Mean Pheo-*a* values did increase with decreasing connectivity, but there were no significant differences across connectivity types. As with chlorophyll-*a*, there was a large amount of variability present in these measurements.

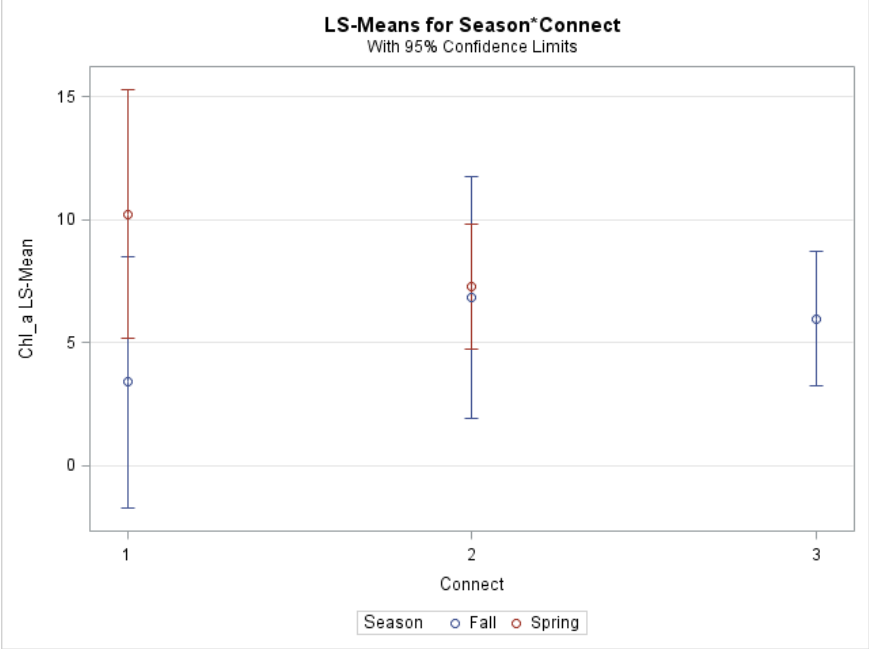

Figure 5.11. Means plot (LS-Means) of chlorophyll-*a* concentrations by season and at different connectivity types (1=fully connected control/main channel, 2=connected secondary channels, 3=disconnected secondary channels).

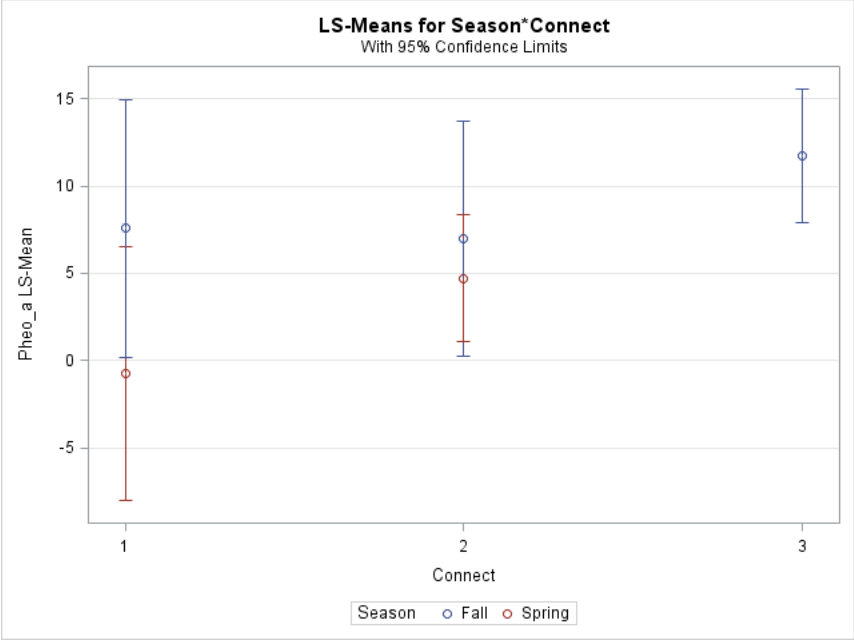

Figure 5.12. Means plot (LS-Means) of pheophytin-*a* concentrations by season and at different connectivity types (1=fully connected control/main channel, 2=connected secondary channels, 3=disconnected secondary channels).

Sediments

Metric multidimensional scaling (mMDS) of sediment metrics, including physical and chemical parameters resulted in an ordination that did not show clear seasonal effects on sediments sampled (Figure 5.14). When labeled for connectivity type (fully connected control/main channel, connected secondary channel, disconnected secondary channel), an obvious grouping of main channel and connected secondary channels is visible along MDS1, with disconnected secondary channel samples falling out in the other direction (Figure 5.15).

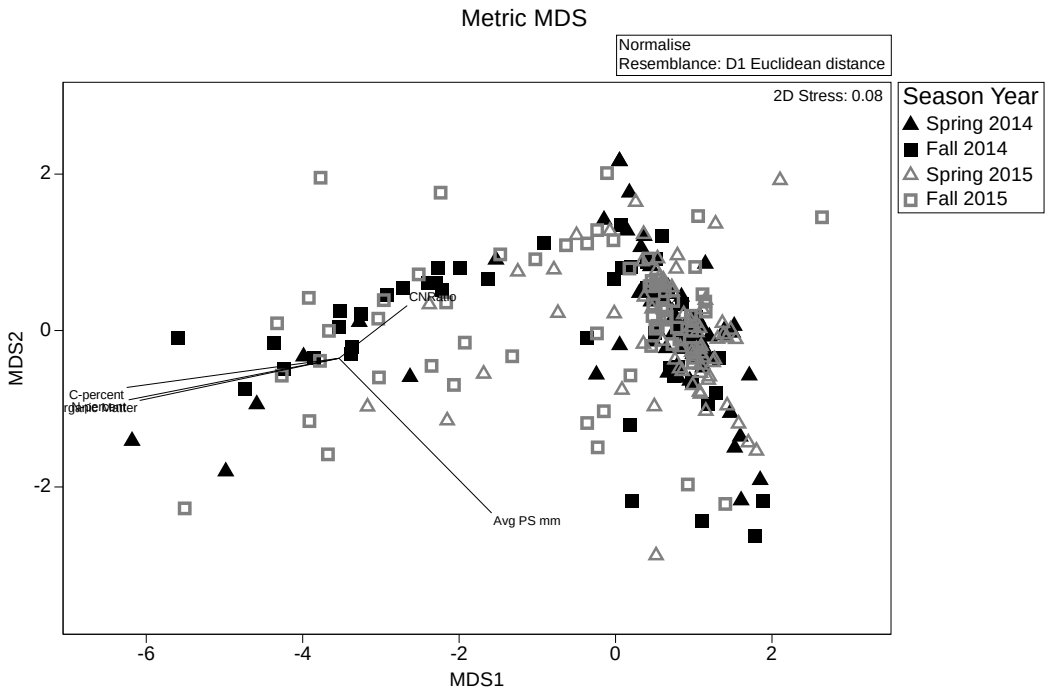

Figure 5.14. mMDS ordination of sediment physiochemical metrics for each sample labeled by season and year collected.

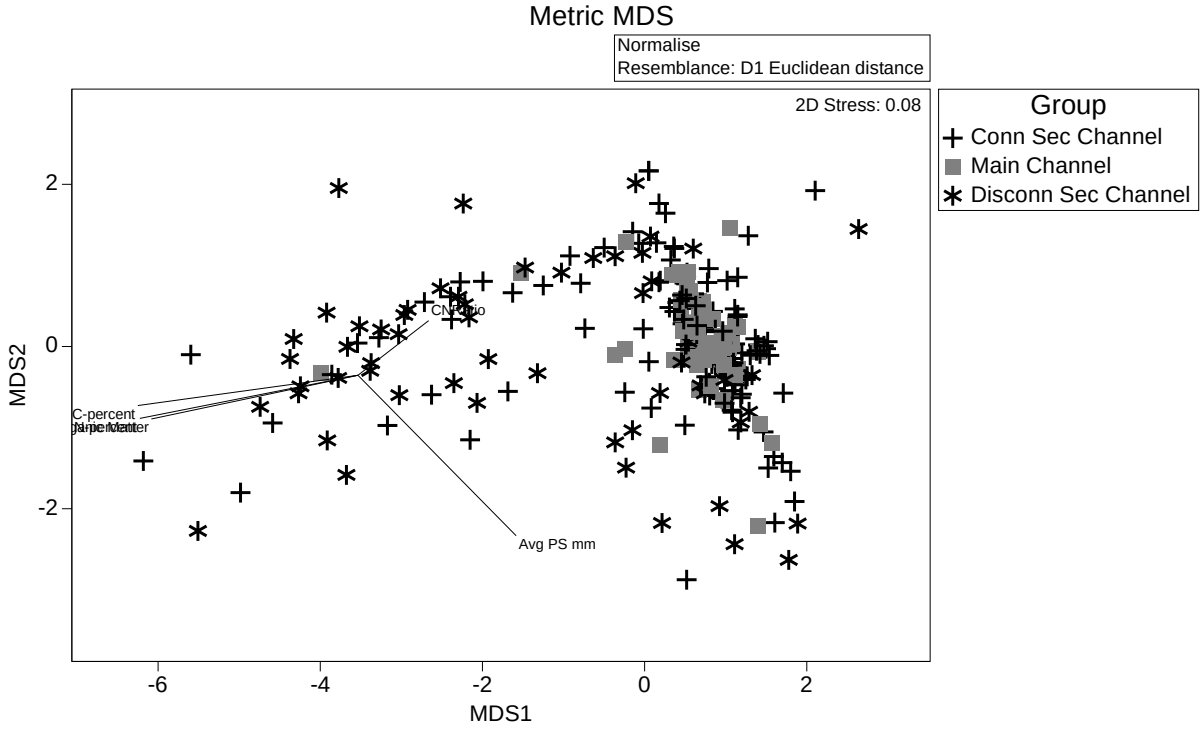

Figure 5.15. mMDS ordination of sediment physiochemical metrics for each sample labeled by connectivity grouping (main channel/fully connected, connected secondary channel, disconnected secondary channel).

Multivariate analysis of variance (MANOVA) resulted in significant overall effects of season (Wilks' Λ=0.952; p=0.016), connectivity (Wilks' Λ=0.722; p<0.0001), and the interaction (Wilks' Λ=0.970; p=.109), on the physiochemical properties of the sediments. The GLIMMIX procedure resulted in significant effects of connectivity (F=12.20; p<0.001) and season (F=4.96; p=0.0314) on the percentage of carbon present in sediments. Carbon content was lowest in main channel sites, with increased mean values found in secondary channels, both connected and disconnected (Figure 5.16). Percent carbon in connected secondary channels differs by season, however, indicating that some carbon content is likely washed out of connected channels during high flows. There were no significant seasonal (F=0.06; p=0.938) or connectivity (F=0.17; p=0.678) effects on the ratio of carbon to nitrogen, which is used to estimate the source of organic matter (allochthonous vs. autochthonous), which is likely due to high variability in the measurements (Figure 5.17; Table 2).

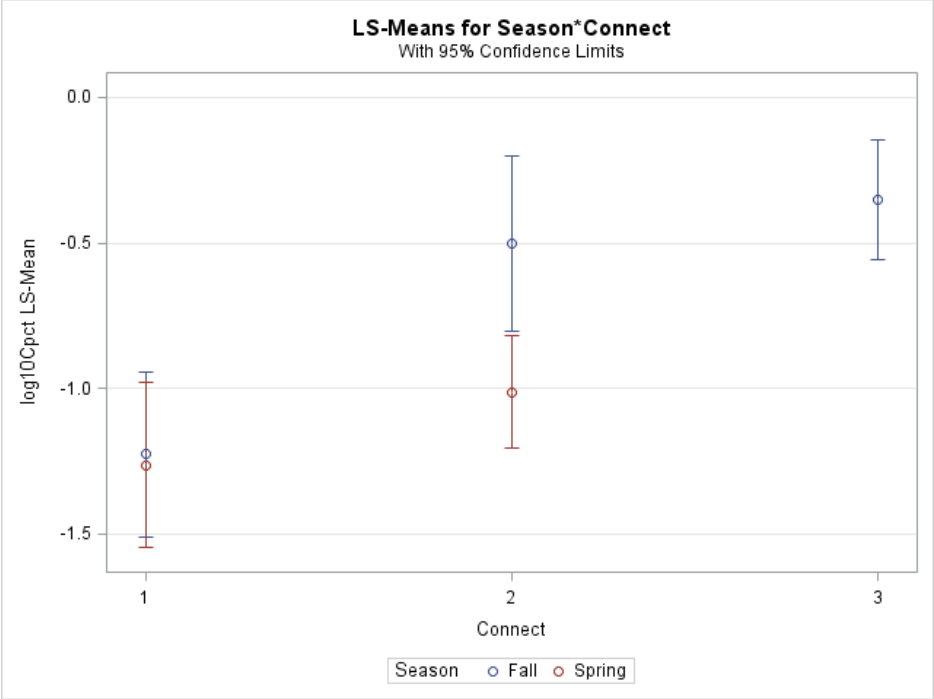

Figure 5.16. Means plot (LS-Mean) for %C (log-transformed) by season and connectivity type (1=fully connected control/main channel, 2=connected secondary channels, 3=disconnected secondary channels).

Table 5.2. LS-Means (95% confidence interval) of sediment physiochemical metrics for each connectivity group and season. Means of log-transformed variables were back transformed and letters to the right of the numbers represent statistical differences between groups in that row based on Tukey HSD tests.

	Season	**1**	**2**	**3**
		Main Channel	Connected Sec. Chann.	Disconnected Sec. Chann.
% Carbon	Spring	0.05 (0.03, 0.16) **a**	0.10 (0.03, 0.24) **b**	-
	Fall	0.06 (0.03, 0.17) **a**	0.32 (0.16, 0.94) **a**	0.45 (0.16, 1.15) **b**
C:N	Spring	15.39 (4.62, 37.38)	20.03 (3.76, 44.69)	-
	Fall	17.49 (5.25, 42.48)	15.14 (5.65, 39.28)	15.61 (3.69, 36.06)
% Organic Matter	Spring	0.39 (0.13, 0.98)	0.60 (0.15, 1.40)	-
	Fall	0.39 (0.14, 1.00) **a**	1.15 (0.47, 3.10) **b**	1.08 (0.60, 5.05) **b**
Average PS (mm)	Spring	0.39 (0.30, 0.47)	0.39 (0.34, 0.45)	-
	Fall	0.36 (0.27, 0.44)	0.25 (0.16, 0.34)	0.30 (0.24, 0.36)

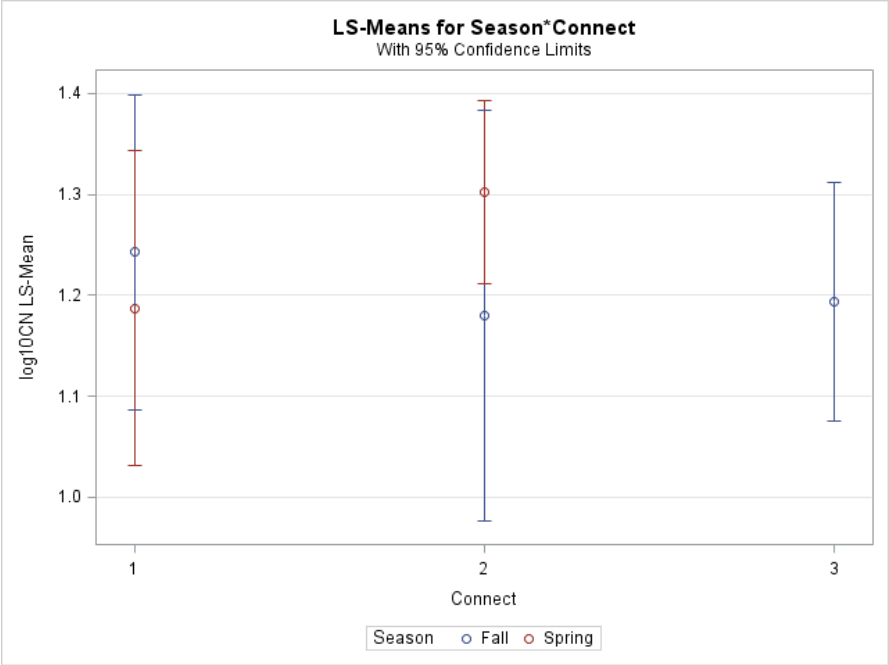

Figure 5.17. Means plot (LS-Mean) for C:N (log-transformed) by season and connectivity type (1=fully connected control/main channel, 2=connected secondary channels, 3=disconnected secondary channels).

There was an effect of connectivity on percent organic matter (%OM) in sediment samples ($F=17.79$; $p<0.0001$), and a possible seasonal influence ($F=2.56$; $p=0.119$). Main channel sites had consistently low %OM in both spring and fall samples (Figure 5.18). Connected secondary channels had higher mean %OM than main channel sites in both spring and fall (Table 5.2). Disconnected secondary channels were highest in %OM, likely a result of fine sediment/detrital deposition coupled with algal production and death. Like the increased %C in sediments, increased %OM is temporary, as less organic matter is present in spring samples. However, an increase in %OM in connected secondary channel sediments compared to main channel sediments highlights the importance of these habitats as a source of nutrition for benthic organisms.

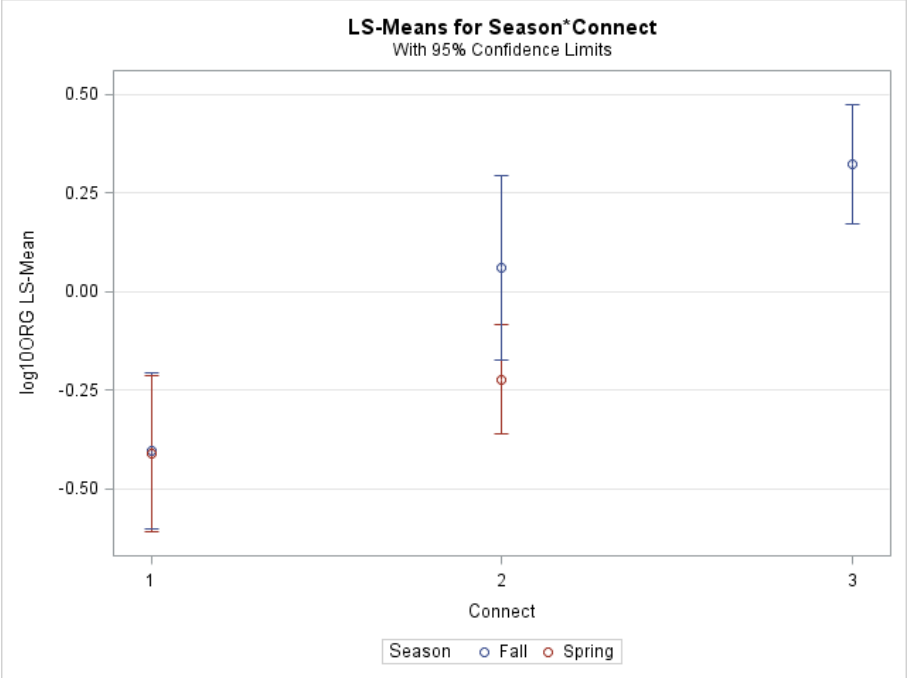

Figure 5.18. Means plot (LS-Mean) for % organic matter (log-transformed) by season and connectivity type (1=fully connected control/main channel, 2=connected secondary channels, 3=disconnected secondary channels).

There was no significant connectivity effect (F=0.69; p=0.509) on average particle size (mm) of sediments, but there was a seasonal effect (F=5.09; p=0.0285). Main channel sediments were on average larger than secondary channel sediments, particularly during fall, when the Mississippi River typically has lower water velocities, allowing smaller particles to fall out along channel borders and in secondary channels, connected and disconnected (Figure 5.19). These data were highly variable, and these average particle sizes are underestimates due to the limitation of sieve mesh sizes available for calculation of weighted averages (e.g., gravel particles were retained by the same mesh size as sand).

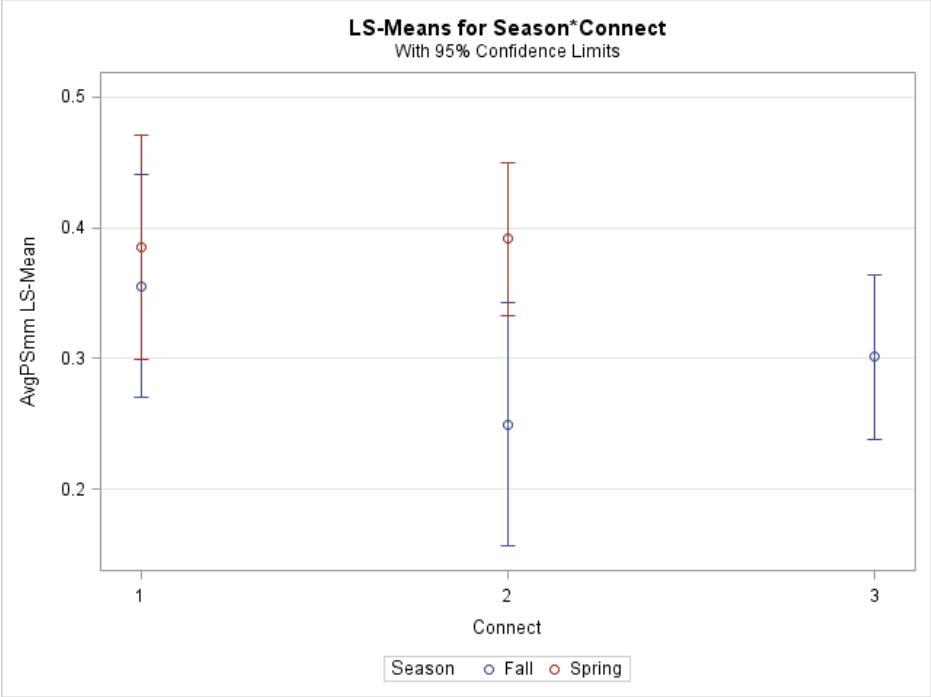

Figure 5.19. Means plot (LS-Mean) for average particle size (mm) of sediments by season and connectivity type (1=fully connected control/main channel, 2=connected secondary channels, 3=disconnected secondary channels).

Conclusions

The Lower Mississippi River floodplain has been reduced in area by approximately 90% due to human modification and control of the system (Baker et al. 1991). There has been some discussion amongst river managers about the value of disconnected secondary channels as temporary backwater/floodplain habitat for biota and nutrient processing. These results suggest that while it is true that disconnected secondary channels have some physiochemical characteristics common in backwater habitats, such as elevated water temperatures and more nutrient rich sediments, these changes are temporary, i.e., not present when sites are fully connected. These results also highlight the importance of connected secondary channel habitat for utilization by the riverine biota. Reduced current velocities, slightly lower turbidities, and higher organic matter all

provide benefits to riverine organisms. Reduction in current velocity provides habitat for mobile organisms such as fish to rest and maintain station, and likely provides a reduction in shear stress on more stationary organisms, including aquatic invertebrates (Lancaster and Hildrew 1993; Sueyoshi et al. 2017; Townsend and Hildrew 1994).

Additionally, these results (and lack of results) raise concerns about bioavailability of nutrients and survivability of primary and secondary producers in what has always been considered a nutrient-dense system. Fine-scale measurements of carbon and nitrogen isotopes were attempted as part of this study, and neither was possible due to undetectable concentrations of these elements in Lower Mississippi River sand sediments. Pigment analyses were also attempted to glean information about the benthic food resource in sandy substrates, and were unsuccessful. This information coupled with low values of percent organic matter and carbon and nitrogen in the sediments raise concerns about sediment nutrient dynamics in the main channel itself. Is the Mississippi River nutrient limited? Rephrased, have we removed the capability of the River to process and sink nutrients?

These are questions that can only be answered with more detailed study and more rigorous data collection. This study does indicate, however, that overall, sediment nutrient concentrations are low, and nutrients present in the water column are not necessarily bioavailable to the benthos. The causes of this are likely multifaceted and could be attributed to many anthropogenic factors/modifications, including: shortening of the Mississippi River for navigation, constraining the river through the construction of levee system, and nutrient pollution of this watershed through under regulated agricultural practices, both historic and current. With a shortened, narrowed corridor,

sufficient nutrient uptake through natural processes is likely impossible. To combat this problem, future restoration efforts should focus on increasing the structural complexity of the channel, increasing the connectivity of the Mississippi River to its floodplain, and increase the water residence time in true backwater habitats.

CHAPTER VI: RARELY COLLECTED LARGE RIVER INSECTS

ABSTRACT

Sampling the Lower Mississippi River main channel and secondary channels during 2014-2015 resulted in the collection of larvae of six mayfly species that specialize in large river habitats. Some of these mayflies are collected in large numbers when encountered, while others are infrequently collected and always in low numbers. Two species, *Raptoheptagenia cruentata* (Walsh) and *Cercobrachys* (nr.) *serpentis* Soldán (Insecta: Ephemeroptera) are reported for Mississippi for the first time. Updated distributions are presented and include records available in major collections and published literature. The apparent restriction of these taxa to large river environments highlights the need for implementation of conservation and restoration efforts to ensure their persistence.

Introduction

Large river habitats are notoriously difficult to sample for macroinvertebrates, which makes successful sampling efforts exciting and worthwhile. Especially exhilarating is the opportunity to encounter taxa rarely collected due to their restriction to large rivers. Large river invertebrates have unique adaptations for maintaining station, feeding, and oviposition in seemingly inhospitable habitats (Blettler et al. 2014; Craig and Chance 1982; Deutsch 1984; Fremling 1960; Hynes 1970; Soluk and Craig 1990). Examples of these adaptations include observations of ovipositing female hydropsychid caddisflies diving and swimming to the bottom to secure eggs directly to the substrate at depths of 8 m in the Upper Mississippi River (Fremling 1960). Additional examples

include the manipulation of flow to vortex feed by a predatory mayfly species (Soluk and Craig 1990), and the finding of larval Chironomidae and aquatic worms ingesting and attaching sand grains to their bodies in order to increase their specific weights and then releasing them when hydrologic stresses ease (Blettler et al. 2014; Marchese 1984; Wantzen et al. 2014). Almost certainly, other behaviors unique to large river insects remain undiscovered.

During the course of sampling for this project, several rarely collected insect taxa, including mayflies (Ephemeroptera) and midges (Diptera: Chironomidae) were obtained. It seems pertinent to highlight these taxa and update their known distributions. This chapter is limited to the Ephemeroptera taxa, because at this point, species level identifications are not available for the chironomid taxa, thus species distributions cannot be easily compiled. These organisms could all be considered stenoecious; many are members of the psammophilic community, living on and within shifting sand in large rivers. This habitat restriction is apparent in their geographical distributions (e.g., Great Plains and Southern Coastal Plains) resulting from the geological events responsible for creating this unique habitat (McCafferty 1991). Other rare species presented herein are specialists in gravel bars and natural clay banks in large rivers, which could be considered the most endangered habitats in the Lower Mississippi River. The rarity of these taxa relative to other groups, and their specialization in large river environments highlights the need for protecting and restoring these habitats to maintain the biological diversity and integrity of large rivers.

Methods

Specimens of the taxa considered here were collected using a benthic sled and subsequently preserved as outlined by Harrison et al. (*in press*). Preserved specimens were identified in the laboratory using an Olympus SZX16 stereo microscope. Most identifications were made using *The Aquatic Insects of North America* (Merritt et al. 2008) and *Larvae of the Southeastern USA Mayfly, Stonefly, and Caddisfly Species* (Morse et al. 2017). Previous collection records were compiled from published literature and from online collection databases (see Appendix D for reference list). Obviously, this is not an exhaustive list, as it is impossible to know if one has included all available collection records. Specimen locality data were georeferenced using Google Maps and approximate GPS coordinates were assigned to map species distributions using ArcGIS version 10.5. For records in which only a county name was included, GPS coordinates were assigned from the nearest major waterway and noted in Appendix D. Specimens of these taxa are currently vouchered at the US Army Engineer Research & Development Center, Vicksburg, MS.

List of Collections/Institutions:

ERDC – US Army Engineer Research & Development Center, Vicksburg, Mississippi

PERC – Purdue Entomological Research Collection, Purdue University, Indiana

INHS – Illinois Natural History Survey, University of Illinois, Champaign-Urbana, Illinois

BCP/USGS – Barry C. Poulton Collection, US Geological Survey, Columbia Environmental Research Center, Columbia, Missouri

CSUC – C.P. Gillette Museum of Arthropod Diversity, Colorado State University, Fort Collins, Colorado

FDEP – Florida Department of Environmental Protection

SEMC – Snow Entomological Museum Collection, University of Kansas Biodiversity Institute, Lawrence, Kansas

IA DNR – Iowa Department of Natural Resources

Rarely Collected Taxa

Cercobrachys (nr.) *serpentis* Soldán 1986 (Ephemeroptera: Caenidae) (Figure 6.1)

In North America, the mayfly family Caenidae, the squaregill mayflies, is represented by six genera. *Cercobrachys* specimens can be distinguished from other Caenidae by the presence of a row of long setae on the foretarsi, and in North America, by the medially curved projection of abdominal segment 6 (Sun and McCafferty 2008). Specimens of *Cercobrachys* collected from the Lower Mississippi River key most closely to *Cercobrachys serpentis* using the most recent literature (Sun and McCafferty 2008), considering morphology of the galealacinia, presence of approximately 50 hairs on the dorsal margin of the hind tibia, and triangulate middle ocellar tubercle. However, the size and shape of the galealacinia slightly differs from the measurements listed in the key, and these specimens could be closely related to *C. etowah*, which has been encountered in Georgia, Florida, Indiana, North Carolina, South Carolina and Wisconsin. The nearest collection of *Cercobrachys serpentis* specimens is from southeastern Nebraska (Figure 6.1), extending the range of this species southeast by approximately 825 kilometers.

Collection of adult *Cercobrachys* specimens is necessary to confirm the species identification. Unfortunately, comparative adult material is scarce, with only one known adult collected from a spider web (L. Jacobus, pers. comm.). Brachycercine mayfly larvae occur in sandy portions of rivers and streams, sometimes blanketed by very thin layers of silt (Edmunds et al. 1976). This is consistent with Lower Mississippi River collections; all larvae were encountered in sandy substrates with some gravel. Collection depths in the LMR ranged from 2.25 – 7.2 m and water velocities ranged from 0.43-0.91 m/s.

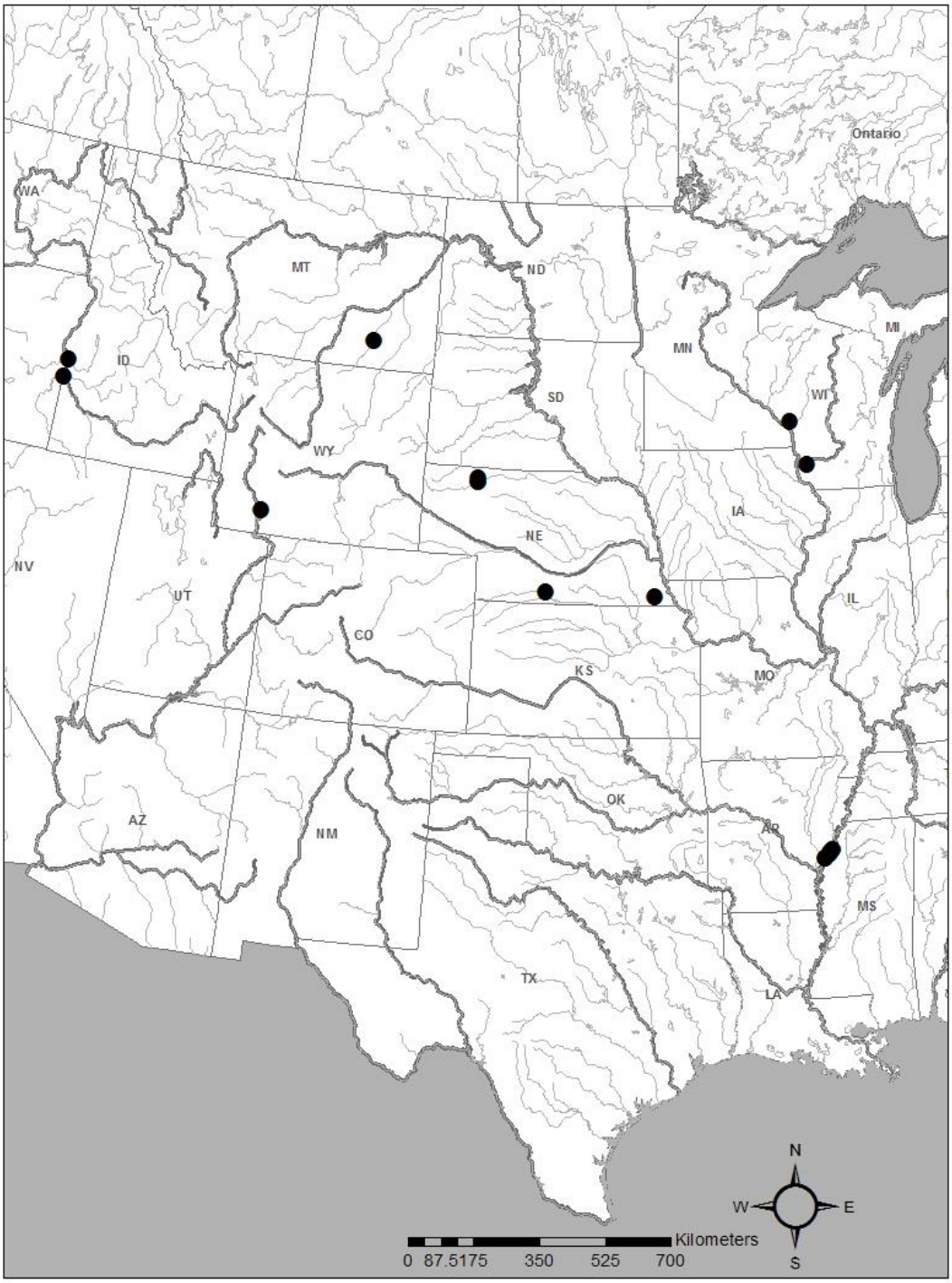

Figure 6.1. Distribution of *Cercobrachys* (nr.) *serpentis* (Ephemeroptera: Caenidae) in central and western North America. Dark gray lines denote major waterways.

Published Records: *see Appendix D, Table D.1.*

New Records: **MS: Coahoma Co.:** Mississippi River, Friars Point Secondary Channel, 34.3735 -90.6473, 24.vi.2015, 1 L; same site, 34.3740 -90.64711, 24.vi.2015, 1 L; Mississippi River, Island 63 Secondary Channel, middle reach, 34.29236 -90.72002, 19.viii.2015, 2 L; Mississippi River, Island 63 Secondary Channel, lower reach, 34.26728 -90.75467, 19.viii.2015, 1 L; Mississippi River, Sunflower Dikes Secondary Channel, 34.17079 -90.89156, 20.viii.2015, 1 L; same site, 34.1715 -90.89221, 20.viii.2015, 3 L.

Raptoheptagenia cruentata (Walsh 1863) (Ephemeroptera: Heptageniidae) (Figure 6.2)

Raptoheptagenia is a monospecific genus in the mayfly family Heptageniidae (Jacobus and Webb 2013; McCafferty 1988; Whiting and Lehmkuhl 1987). Its distinctive ventral gill patterns make it easily distinguishable from other heptageniids. This species is a predator collected sporadically in and around medium – large rivers across North America, where can move very quickly across the substrate (Edmunds et al. 1976; Stagliano 2006; Waltz et al. 1998). Although rarely collected compared to other heptageniid taxa, previous collections of *R. cruentata* specimens suggest it can occur in large numbers where present (Stagliano 2006). The associated habitat with this species is gravel with underlying sand, which is consistent with collections from the Lower Mississippi River. Currently, this is a “Species of Concern” in Montana along with other mayflies occupying its microhabitat (Stagliano 2016).

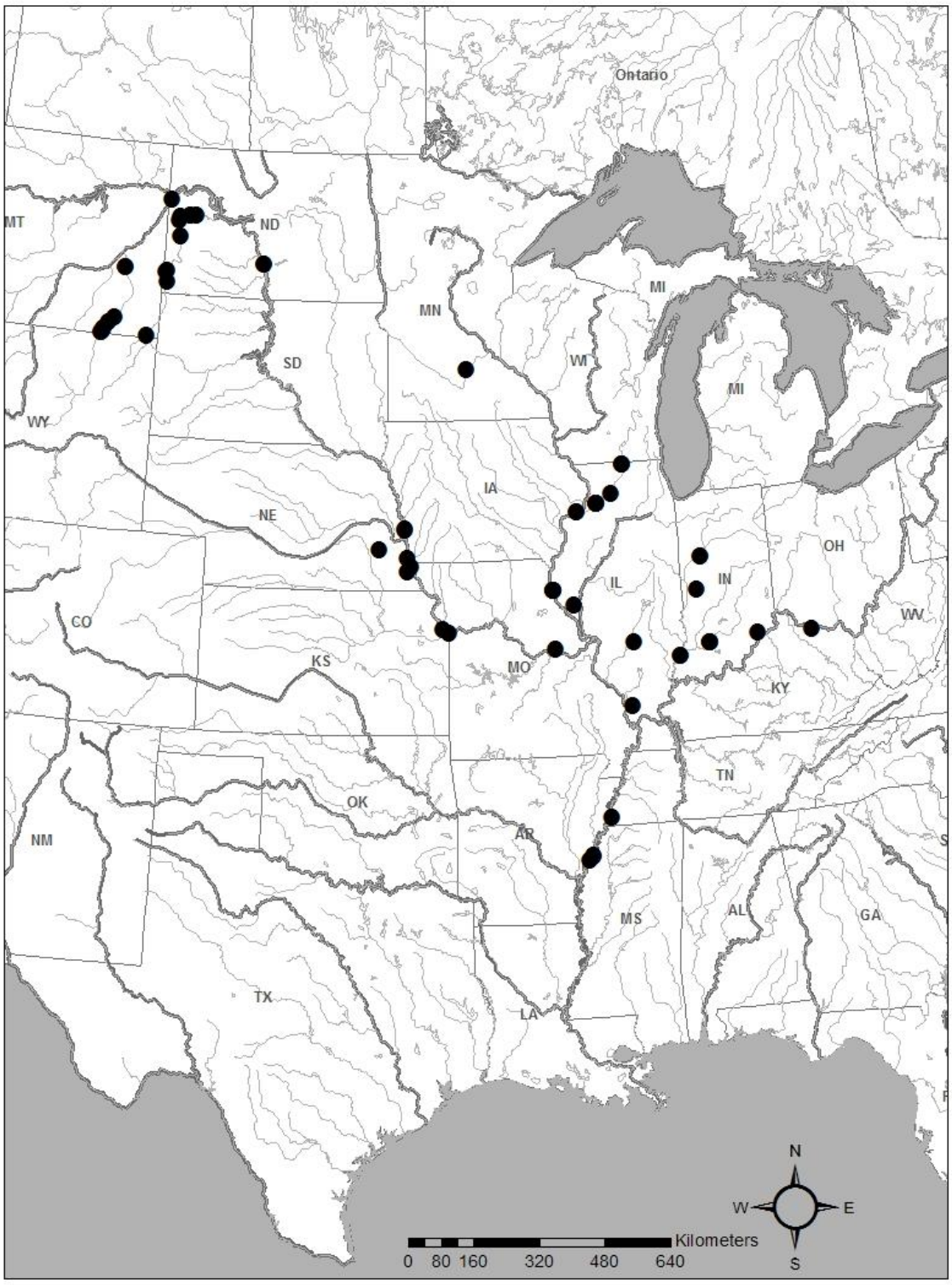

Figure 6.2. Distribution of *Raptoheptagenia cruentata* (Ephemeroptera: Heptageniidae) in central North America. Dark gray lines denote major waterways.

Previous collection records: *see Appendix D, Table D.2.*

New records: **AR: Phillips Co.**: Mississippi River, Island 62 Secondary Channel, 34.29314 -90.75492, 11.vi.2014, 3 L; **MS: Coahoma Co.:** Mississippi River, Friars Point Secondary Channel, 34.37409 -90.64619, 12.vi.2014, 1 L; Mississippi River Main Channel, 34.38725 -90.64260, 24.vi.2015, 1 L.

Spinadis simplex (Walsh 1863) (Ephemeroptera: Heptageniidae) (Figure 6.3)

Spinadis is another monospecific genus in the family Heptageniidae that is rarely collected in larval or adult form, and has an unusual larval form compared to other heptageniids. In fact, when the larvae were first discovered, the authors, within the generic description, remarked that they were "so distinctive that it was uncertain at first to what family they belonged" (Edmunds and Jensen 1974). Unlike most other heptageniids, *Spinadis* has a fusiform body and tail setae indicating it is likely a swimmer (McCafferty et al. 2017). The mouthparts suggest that larvae are predatory. This genus can be separated from other heptageniids by the presence of only two caudal filaments with interfacing setae, two tubercles on the head, and relatively long legs with only sparse setae (Webb and McCafferty 2008). In the LMR, this species occurred over a mixture of sand, large gravel, and mud, in a secondary channel with 0.91 m/s current velocity.

Figure 6.3. Distribution of *Spinadis simplex* (Ephemeroptera: Heptageniidae) in eastern North America. Dark gray lines denote major waterways.

Previous collection records: *see Appendix D, Table D.3.*

New record: **MS: Coahoma Co.:** Mississippi River, Friars Point Secondary Channel, 34.37297 -90.64755, 24.vi.2015, 1 L.

Pseudiron centralis (McDunnough 1931) (Ephemeroptera: Pseudironidae) (Figure 6.4)

Pseudiron is a monospecific mayfly genus inhabiting medium to large rivers in North America, and is listed as threatened in parts of its range (Harris 1990; Pescador 1985; Peters 1994). It is a predatory species adapted to shifting sand substrata, which is consistent with Lower Mississippi River collections (Long and Kondratieff 1996; Sanders and Bingham 1980; Soluk and Craig 1990). As described above, it feeds on unsuspecting prey by manipulating the flow of water over its body, creating a vortex (Soluk and Craig 1990). The *P. centralis* larva has long, slender claws, which are used to anchor it into the sand (Pescador 1985). Interestingly, the tarsal claws have a mass of nerve cells at the apical constriction, although the adaptive value of this trait is unknown (Pescador 1985). These could be used to gage water velocity for station holding or flow manipulation. Collection of mature larvae in June suggest a June – July emergence period in the Mississippi River.

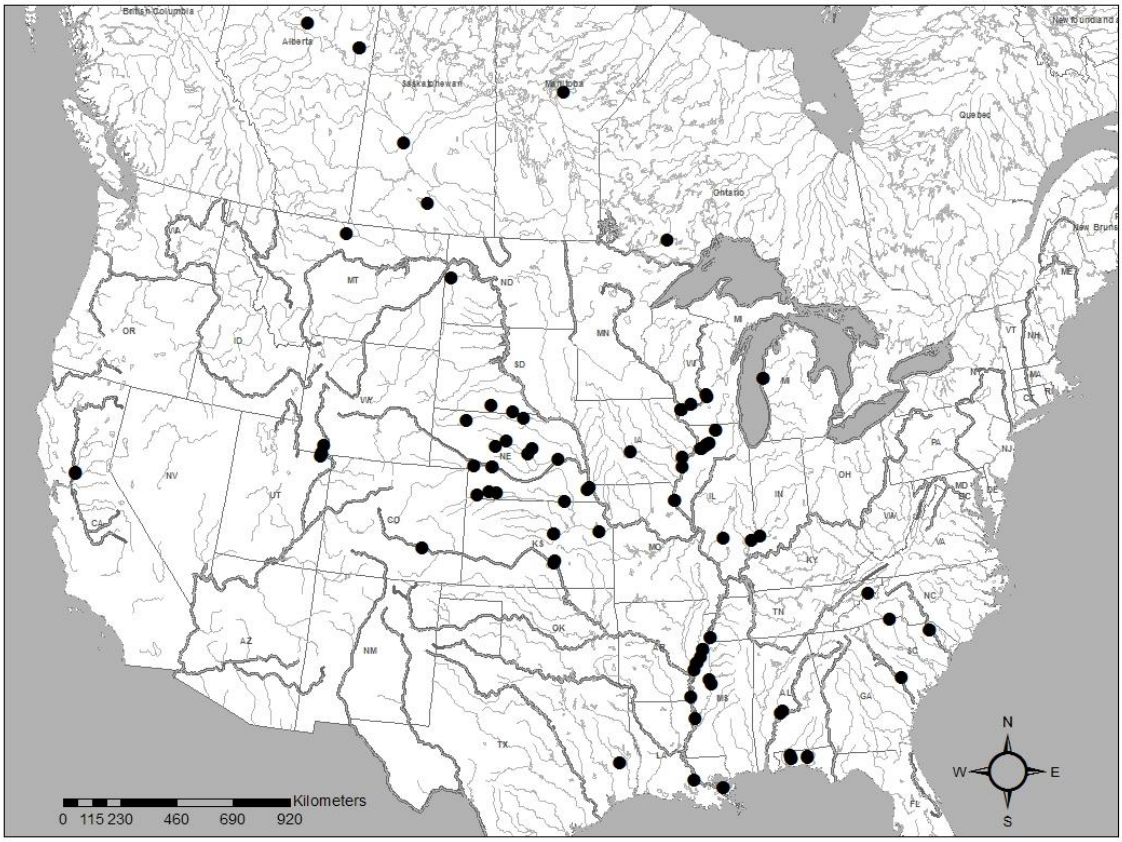

Figure 6.4. Distribution of *Pseudiron centralis* (Ephemeroptera: Pseudironidae) in North America. Dark gray lines denote major waterways.

Previous collection records: *see Appendix D, Table D.4.*

New records: **AR: Lee Co.:** Mississippi River Main Channel at Mhoon Bend, 34.73798 -90.46111, 10.v.2007, 4L; **Phillips Co.:** Island 62 Secondary Channel, 34.29114 -90.75568, 11.vi.2014, 2 L; **MS: Bolivar Co.:** Knowlton Secondary Channel, 34.0329 -90.90246, 11.vi.2014, 1 L; **Coahoma Co.:** Friars Point Secondary Channel, 34.3742 -90.364642, 12.vi.2014, 1 L; Mississippi River Main Channel, 34.50586 -90.57893, 12.vi.2014, 1 L; **Warren Co.:** Mississippi River Main Channel below Vicksburg, 32.24256 -90.96735, 1.vi.2007, 1 L.

Tortopsis spp. (Molineri 2010) (Ephemeroptera: Polymitarcyidae) (Figure 6.5)

The genus *Tortopsis* (Polymitarcyidae) is comprised of seven known species (2 North American species) that are infrequently collected in larval form (Molineri 2008, 2010). *Tortopsis* is distributed throughout North, Central, and South America, and larvae are known to create U-shaped burrows with parallel arms in clay banks of rivers (Edmunds et al. 1976; Molineri 2008, 2010). In suitable habitat, larval burrows, which resemble honeycomb, can be found at every river bend, and occasionally in the banks of river runs (Edmunds et al. 1976). Observations of burrows above the waterline suggest individuals may be able to move up and down into different burrows with changing river stage (Scott et al. 1959). Inside their burrows, larvae position themselves facing one of the entrances and use the long setae on their forelegs and mouthparts to trap organic matter (Molineri 2008; Scott et al. 1959). *Tortopsis* is thought to have a 1-2 year life span to complete larval development (Edmunds et al. 1976; Scott et al. 1959). Mass emergence begins the week of June 6 and ends the week of November 14, with highest numbers occurring with decreased lunar light intensity (Edmunds et al. 1976). Mating flights take place over rivers beginning after sunset and continuing until after midnight/early morning. Currently, there is only one potential diagnostic character used to distinguish between the two North American *Tortopsis* species as larvae (McCafferty 1975). The anterolateral horns of the frontal shelf extend past the margin of the antennal scapes in *T. puella*, whereas the anterolateral horns do not reach the margin of the antennal scapes in *T. primus*. While *T. primus* has a more central/western North American distribution (McCafferty 1994) than *T. puella*, and has not been previously collected in Mississippi, the LMR may represent the eastern edge of the range (Figure 6.5). Larvae collected in the

LMR during this study have anterolateral horns that do not reach the margin of the antennal scapes, however no mature larvae have been obtained. Consequently, these specimens are being treated as *Tortopsis* spp. until more mature specimens are collected.

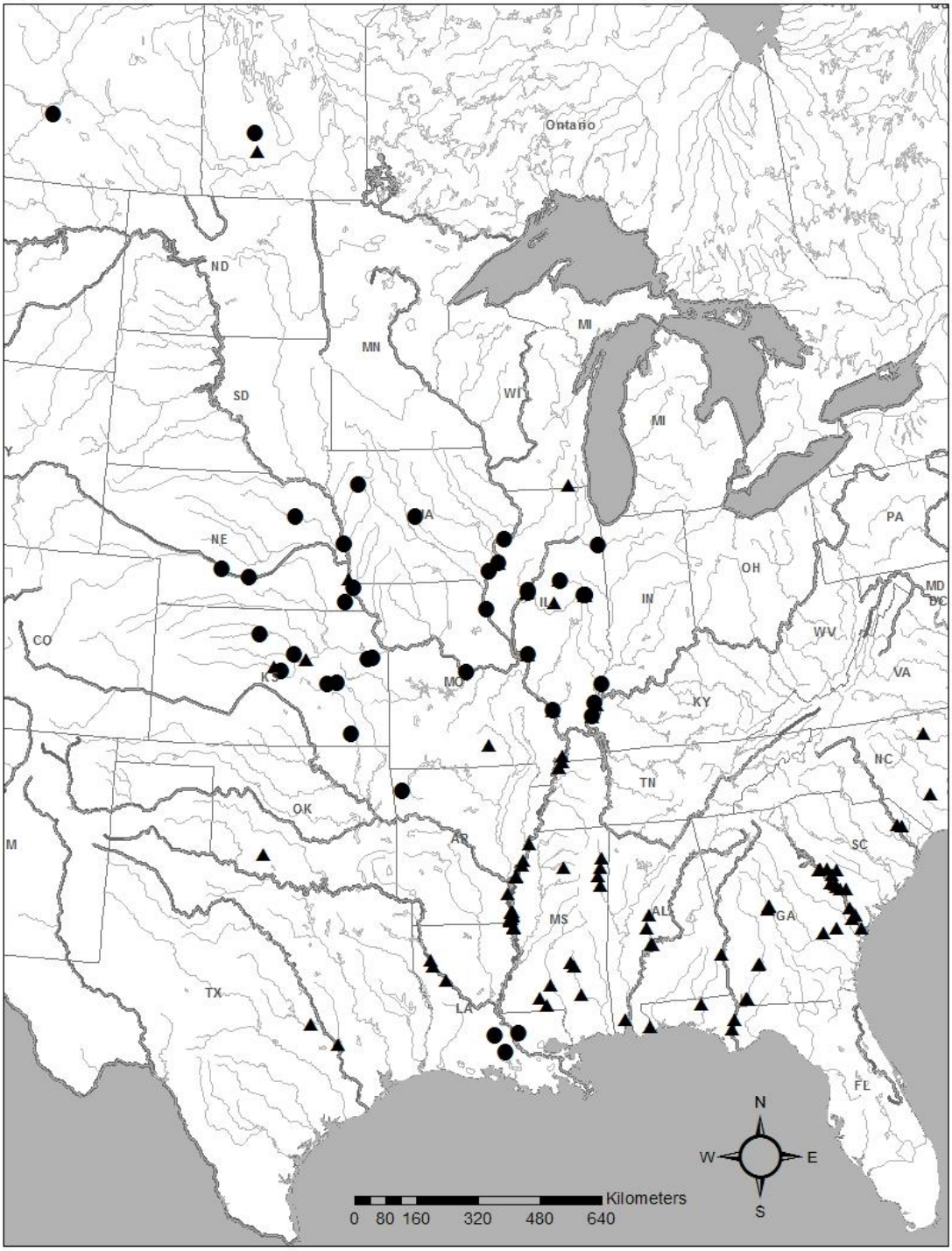

Figure 6.5. Distribution of *Tortopsis* spp. (Ephemeroptera: Polymitarcyidae) in North America. Black circles = *T. primus*; Black triangles = *T. puella*. Dark gray lines denote major waterways.

Previous collection records: *see Appendix D, Tables D.5-D.6.*

New records: **AR: Phillips Co.:** Mississippi River, Kangaroo Point Secondary Channel, 34.37307 -90.70468, 12.vi.2014, 2L; **MS: Bolivar Co.:** Mississippi River, Knowlton Secondary Channel, 34.03062 -90.91422, 4.xi.2014, 1 L; Mississippi River, Hurricane Point/Dennis Landing, 34.01816 -90.94228, 22.x.2015, 3 L; **Coahoma Co.:** Mississippi River, Island 63 Secondary Channel, 32.2683 -90.73325, 11.vi.2015, 20 L.

Pentagenia vittigera (Walsh 1863) (Ephemeroptera: Palingeniidae) (Figure 6.6)

Pentagenia vittigera is the only extant North American representative of the family Palingeniidae. The other known North American species, *P. robusta* was described from the Ohio River (McDunnough 1926), known from Ohio and Kentucky, and is thought to have been extirpated due to river modifications (McCafferty 1994). Like *Tortopsis*, *P. vittigera* larvae create U-shaped burrows in honeycomb patterns in clay banks or mud bottoms of large rivers (Berner 1959; Edmunds et al. 1976). In the Lower Mississippi River, this species was encountered primarily in natural steep bank habitat, occasionally in mixed substrates (Beckett et al. 1983a; Mathis et al. 1981), which is consistent with the collections from this study. In the Lower Missouri River, Braaten and Guy (1997) observed thousands of *Pentagenia vittigera* stranded by sudden dewatering events downstream of dikes, and noted the substrate occupied was mud. Larvae filter feed inside their burrows with their heads facing upstream and forelegs flexed into a catchment basket (Keltner and McCafferty 1986). In Europe, a study of *Palingenia*, another genus of Palingeniidae suggested larvae ingest clay and mud particles of a particular size to extract nutrition, expelling particles that are too big or small (Landolt et al. 1995). Adults have been collected between early May and early October (Edmunds et al. 1976). Collection of a wide range of size classes at different

times of year may indicate a lifespan of at least two years. Observed sensitivity of these larvae to rapid dewatering should be considered in management of LMR secondary channels.

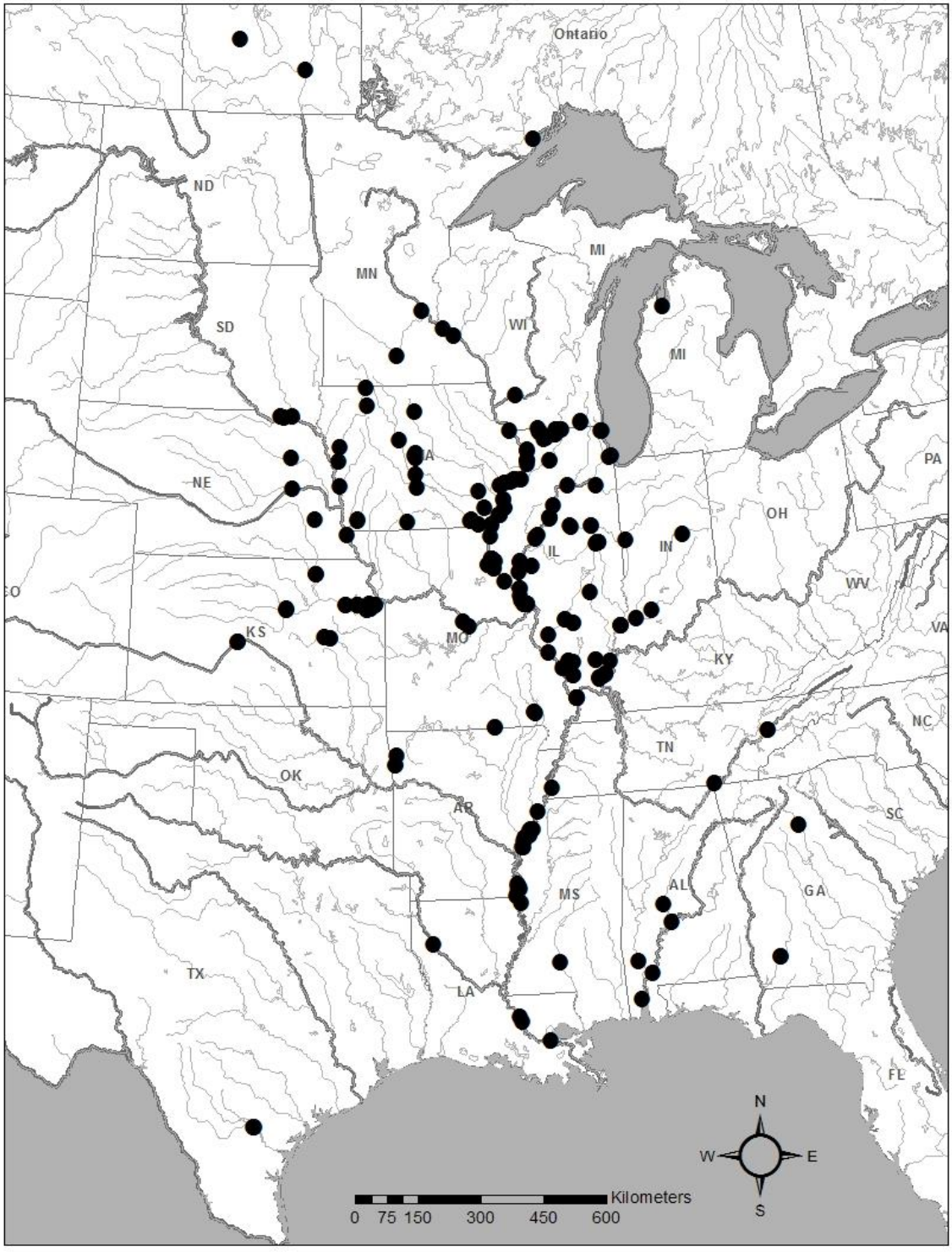

Figure 6.6. Distribution of *Pentagenia vittigera* (Ephemeroptera: Palingeniidae) in North America. Dark gray lines denote major waterways.

Previous collection records: *see Appendix D, Table D.7.*

New records: **AR: Phillips Co.** Mississippi River, Island 62 Secondary Channel, 34.28801 -90.75537, 11.vi.2014, 1 L; same location, 34.29314 -90.75492, 1 L; Mississippi River, Island 64 Secondary Channel, 34.21951 -859474, 20.viii.2015, 5 L; same location, 34.19976 -90.868612, 20.viii.2015, 1 L; same location, 34.19899 -90.86829, 20.viii.2015, 2 L; Mississippi River, Kangaroo Point Secondary Channel, 34.37307 -90.70468, 12.vi.2014, 1 L; same location, 34.37035 -90.71871, 23.vi.2015, 1 L; Mississippi River Main Channel, 34.37463 -90.6804, 12.vi.2014, 1 L; **MS: Bolivar Co.** Mississippi River, Knowlton Secondary Channel, 34.03062 -90.91422, 4.xi.2014, 2 L; Mississippi River, Hurricane Point Secondary Channel/Chevrons at Dennis Landing, 34.01717 -91.94269, 22.x.2015, 1 L; **Coahoma Co.** Mississippi River, Island 63 Secondary Channel, 34.2876 -90.72105, 5.xi.2014, 1 L; same location, 34.28787 -90.72045, 5.xi.2014, 1 L; same location, 34.31672 -90.73232, 19.viii.2015, 15 L; same location, 34.31733 -90.73172, 19.viii.2015, 2 L; same location, 34.31764 -90.73137, 19.viii.2015, 7 L; same location, 34.26721 -90.75510, 19.viii.2015, 12 L; same location, 34.26408 -90.74312, 20.x.2015, 2 L; same location, 34.26408 -90.74323, 20.x.2015, 1 L; Mississippi River Main Channel, 34.15497 -90.91963, 4.xi.2014, 2 L.

Discussion

Large river habitat specialists can be elusive, highlighting the importance of pinpointing microhabitat requirements for more targeted sampling. Their apparent rarity makes it difficult to assess population sizes and security, underlining the need for documentation of occurrences and distributional patterns, both historic and present (Harrison and DeWalt 2017; McCafferty 1991). These insects occupy a variety of microhabitats, including shifting sand, gravel, and compressed clay.

Shifting sand habitat in the Lower Mississippi River (LMR) is abundant, comprising the majority of main channel and island bar habitat (Baker et al. 1991). Although this habitat is common, more research into resource availability for macroinvertebrates is necessary, as it is possible that these habitats are subject to nutrient limitation, affecting the abundance of collectors-gatherers and predatory species (Chapter 5; Hynes 1970). Potential nutrient limitation could impact not only psammophilic

macroinvertebrates, such as *Pseudiron centralis*, but also the fishes that consume them, such as river sturgeon (e.g., Harrison 2012; Harrison et al. 2014; Sechler et al. 2012).

Gravel habitats in the LMR have been affected by the placement of dike structures aimed at creating a self-scouring navigation channel. Construction of dikes in many cases has resulted in deposition of sand along island tips, which blankets gravel substrates in many reaches of the LMR (Biedenharn and Corcoran 2008; Gaines and Priestas 2016). Recently, biologists and habitat managers have made recommendations for modification of these structures to uncover infilled gravel bars to restore this habitat, which is critical not only for large river macroinvertebrates such as mayflies (e.g., *Raptoheptagenia cruentata*) and stoneflies (Harrison and DeWalt 2017), but is also spawning and feeding habitat for various riverine fishes, including federally endangered Pallid Sturgeon (USFWS 2013).

Steep natural bank habitat in the erosional zone of the LMR main channel has effectively been eliminated by the placement of artificial revetments, including rip rap and articulated concrete mattresses (ACM) (USFWS 2013). These structures function to reduce bank erosion, and to maintain the current channel. At present, it is almost impossible to find natural bank habitat in the main channel, except for areas where revetments have sloughed off (personal observation). Additionally, repair work is done by the USACE each year to sink new ACM in these areas, averaging 48091.9 ± 9853.9 linear feet (Killgore et al. 2014). Many secondary channels, however, still possess steep clay banks, and these areas are likely critical habitat for river bank mayflies such as *Pentagenia vittigera* and *Tortopsis* spp. In order to increase the availability of these habitats for use by these and other organisms, secondary channels need to maintain an

upstream connection to the main channel for the duration of their lifespans, as these species require flowing water to filter feed in their burrows.

In conclusion, understanding the life history, habitat associations, and distributional patterns of large river macroinvertebrates is fundamental to their conservation. In the LMR, these include a range of habitat types, ranging from erosional steep banks, the sandy main channel, and gravel and sand bars in depositional areas. Continued monitoring efforts are necessary to inform and guide management and/or restoration of these habitats for use by various organisms.

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CHAPTER VII: SYNTHESIS

Habitat connectivity is a driver of multiple processes across ecosystem types (Amoros and Bornette 2002; Tockner et al. 1999; Thorp et al. 2006). In aquatic systems, such as rivers, hydrological connectivity, or the multidirectional movement of water across space, influences communities and impacts nutrient dynamics at multiple scales (Hein et al. 2005; Thorp and Delong 1994, 2002). Lateral connectivity – unidirectional movement of water from upland sites to the river, or bidirectionally between the main stem and the floodplain – influences the physical habitat, as well as the biotic communities present therein (Baker et al. 1991; Fremling et al. 1989; Pongruktham and Ochs 2014; Ward and Stanford 1995). In the Lower Mississippi River-floodplain system, macroinvertebrates respond to connectivity in different ways, depending on life history strategies. In highly connected (eupotamal) habitats, such as secondary channels, lotic communities are present. Lotic organisms are evolutionarily dependent on flowing water and use the movement of water for a variety of life history processes, including feeding, respiration, and movement via drift (Hynes 1970). In highly disconnected sites, lentic communities are present, and members use a different suite of life history strategies for feeding, respiration, and movement. Problematic for the persistence of macroinvertebrate communities is the change from lotic to lentic and vice versa on a regular basis. In intermediately connected/disconnected habitats, there is a lower diversity of macroinvertebrate taxa. Habitats with intermediate connectivity are not, however, unimportant or without value. These habitats are higher in primary production than the channel, serve as nursery habitat for fishes, and a sink for nutrients (Baker et al. 1991; Hein et al. 2005; Ochs et al. 2013; Pongruktham and Ochs 2014).

Within the Lower Mississippi River proper, longitudinal, or upstream/downstream connectivity affects biological processes occurring in the river's abundant secondary channels. Historically, secondary channels were continually created and lost with the natural movement of the river channel. Today, through human attempted control and management of the river, a finite number of naturally occurring channels remain, and due to imposition of dike structures, we have seen a net reduction in connectivity to main channel flow. Macroinvertebrates respond to intermediate connection in these channels much in the same ways as in floodplain habitats. When channels are disconnected, lotic communities (dependent on continuous flow) are replaced by lentic communities (dependent on lack of flow). In the LMR, these environmental shifts occur suddenly and can happen multiple times within a water year, primarily during low river stages during summer and fall. The shift(s) from lotic to lentic to lotic is often out of sync with insect oviposition periods, limiting the recolonization potential for these habitats when flow is inevitably restored (Ladle and Ladle 1992). Additionally, it is unclear if drifting invertebrates recolonize rapidly over dike structures, as natural invertebrate drift has been found to be more concentrated within the bottom of the water column (Beckett and Kasul 1987). The result is an observable legacy effect within macroinvertebrate community structure when sampling channels across a connectivity gradient, even when channels are all fully connected to main channel flow. The impacts of this legacy effect on higher trophic levels, such as fish, are currently unknown, but it is likely that a reduction in macroinvertebrate diversity, as well as changes in benthic communities, could alter the trophic webs of these habitats.

Connectivity not only influences the macroinvertebrate communities, but also transforms the physiochemical environment of LMR secondary channels. Disconnected secondary channels have physiochemical properties similar to backwater sites. These areas can be highly productive in terms of algal growth, as observed in previous studies (Pongruktham and Ochs 2014). Disconnected channels allow for the uptake of nutrients, such as nitrates and phosphorus, through increased biological production, and due to these processes, have differences in chemical composition of the sediments. These differences, however, are only observed during periods of disconnection and likely only last until reconnection occurs. Of course, these changes do not occur in isolation, and affect the resident communities in several hypothesized ways, including (1) loss of flow for filter feeding, (2) declines in dissolved oxygen levels, and (3) siltation of eggs and larvae occupying course sediments through rapid precipitation of fine particles.

When addressing any question regarding management or restoration of an ecosystem, it is important to first consider the evolutionary process that shaped the physical habitat and its biological communities. Over its evolutionary history, the Lower Mississippi River was dynamic, changing in morphology, force, and function (Baker et al. 1991; Benke and Cushing 2005; Morris 2016). Coevolving with its patterns of geomorphological and hydrological changes were its biological communities, adapting to spatial and temporal variation in habitat structure. Humans have and still attempt to halt the evolution of the LMR system, and to simplify it for limited objectives, by almost eliminating its floodplain, cutting off its meander bends, and preventing its migration (Alexander et al. 2012). These changes have affected riverine and floodplain

communities in many ways, including disruption of multidirectional hydrologic connectivity within the system.

Today, managers are seeking to rehabilitate some of the habitats affected by human change, and are employing scientists to steer their progress through research (Killgore et al. 2014; USFWS 2013). Results of this study can, in a small way, guide the rehabilitation of floodplain and backwater habitats in the Lower Mississippi River system, by serving as a reminder that ecological communities are a product of their evolution within the system, as well as a driver of future changes. To maintain riverine communities, habitats must remain riverine; to maintain backwater communities, backwaters must remain disconnected for large parts of the year – the frequency, duration, and periodicity of connection is key. Recommendations from this study include:

(1.) Creation of paleopotamal habitat. Due to the restriction of the floodplain, paleopotamal sites within the batture are rare. These habitats host communities not found in intermediately or fully connected habitats. This can be achieved by creating pool habitats with increased connection thresholds and water surface elevations in mind.

(2.) Increased secondary channel connectivity. Secondary channels are naturally riverine and are colonized by lotic organisms. In order to maintain permanent macroinvertebrate communities throughout the year, secondary channels need to have permanent flow. This can be achieved by lowering connection thresholds by notching or removing dikes, and by creating pilot channels with year-round flow, albeit a smaller area. The addition of pilot channels to secondary channels should allow for heterogeneity in flow patterns, in order

to maximize the substrate diversity, and therefore a higher diversity of riverine residents.

Finally, there is still much to be learned about this system, and scientists have only scratched the surface in the understanding of its processes or its trajectory. More research is necessary to fully understand this and other large rivers, such as how the river is changing with respect to vertical connectivity (surface/groundwater interactions) in a time when nearby aquifers are being depleted, how habitat alteration and land conversion throughout the Mississippi River Basin has affected the sediment load and inputs of allochthonous material in the form of large woody debris, how preventing erosion along channel borders has/is affecting communities, and how communities are responding to current restoration efforts. These areas of research are critical to the understanding of the Lower Mississippi River, its function, and its value to the many species that depend on it, including us.

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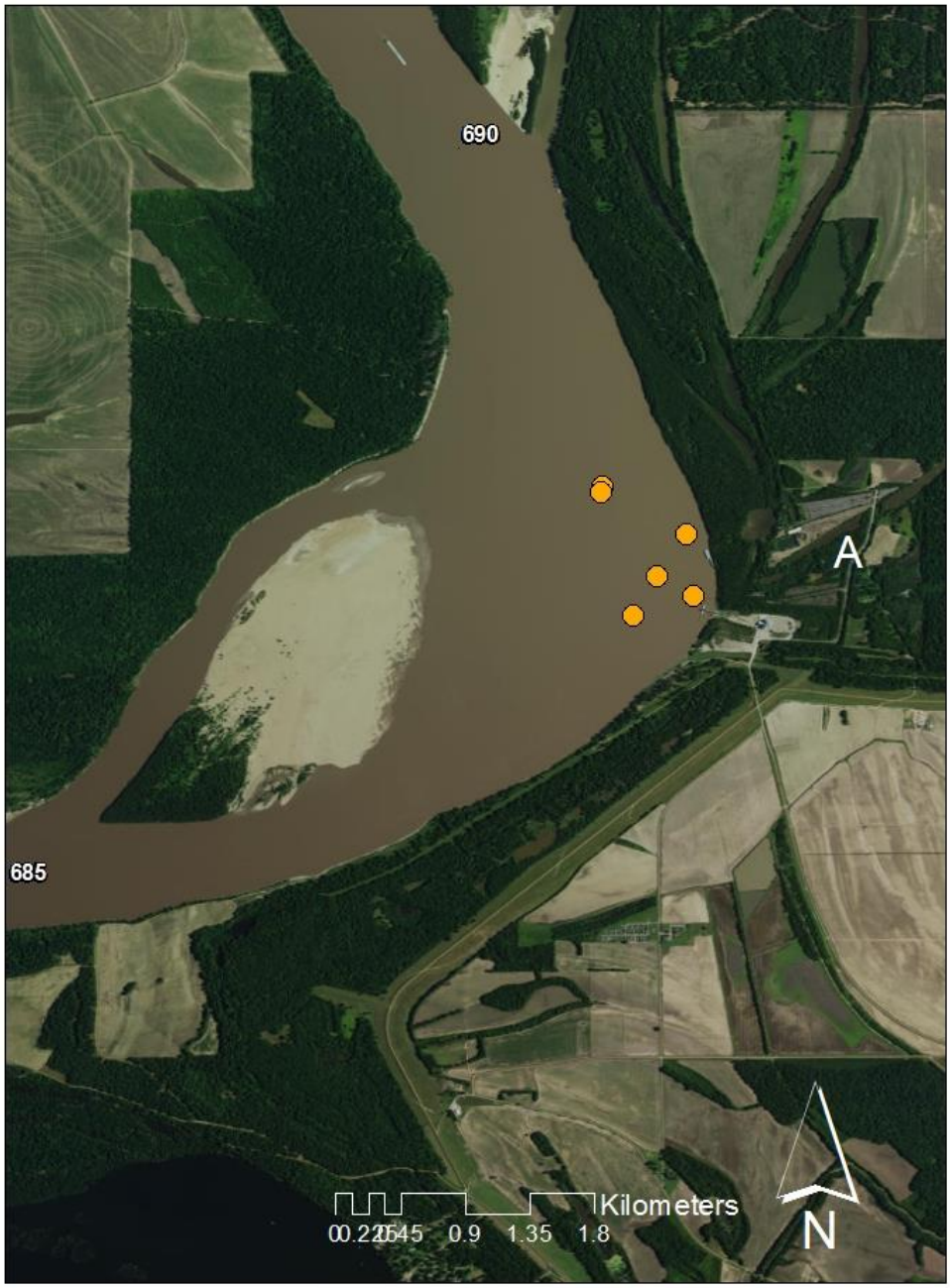
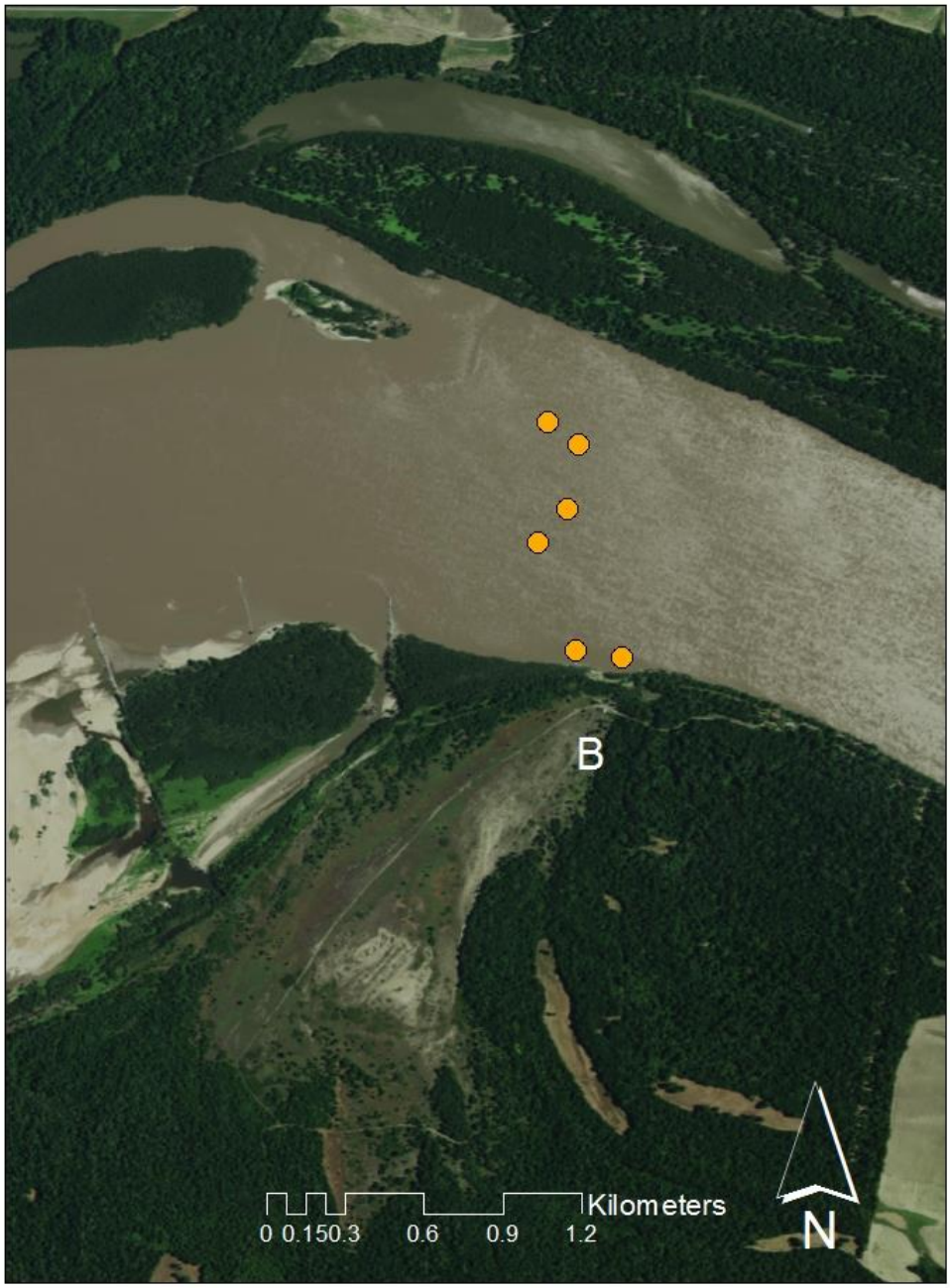
APPENDIX A: SITE MAPS

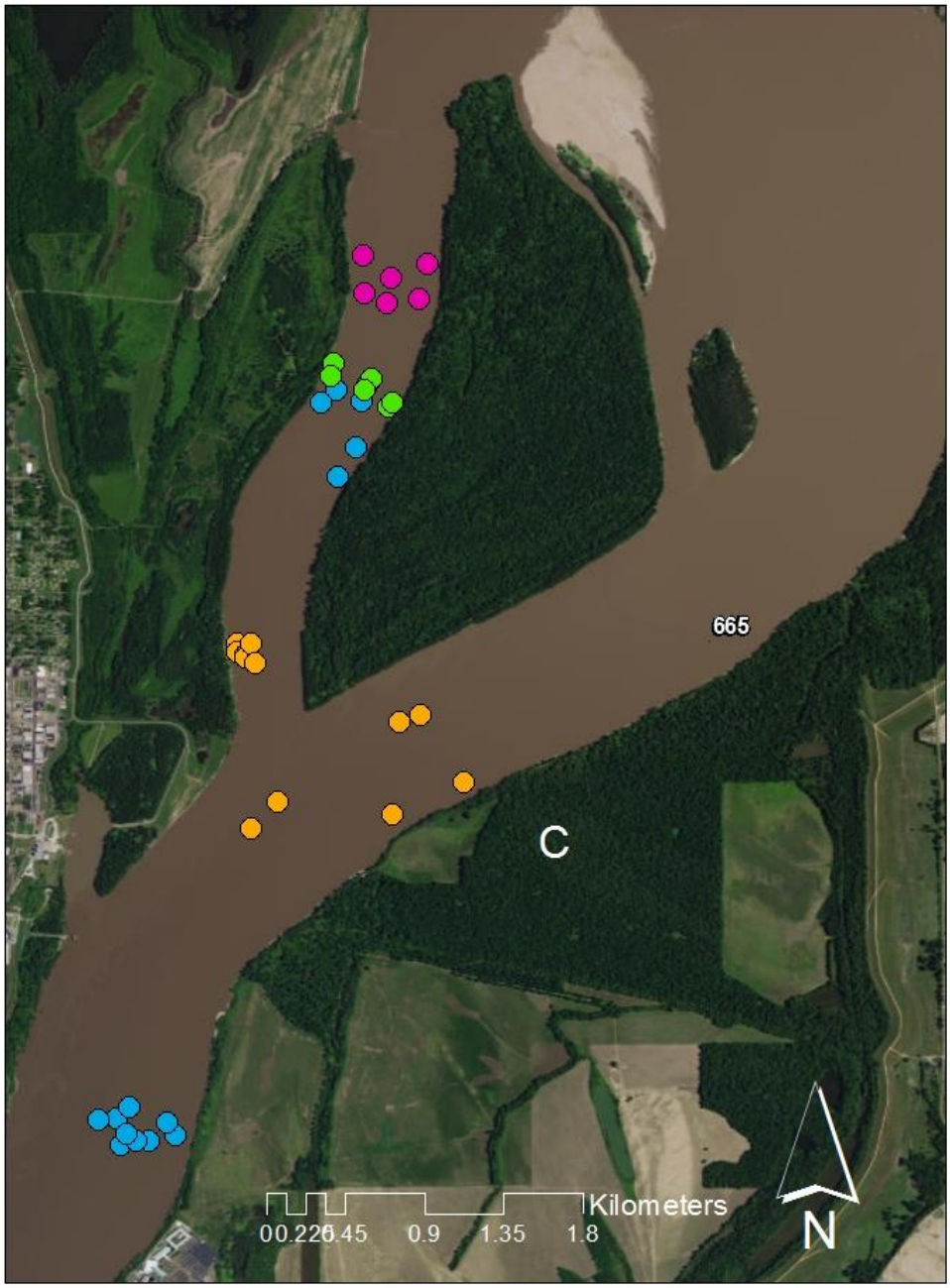
Map A. Mississippi River at Mhoon Bend, near Tunica, MS (RM 685-691).



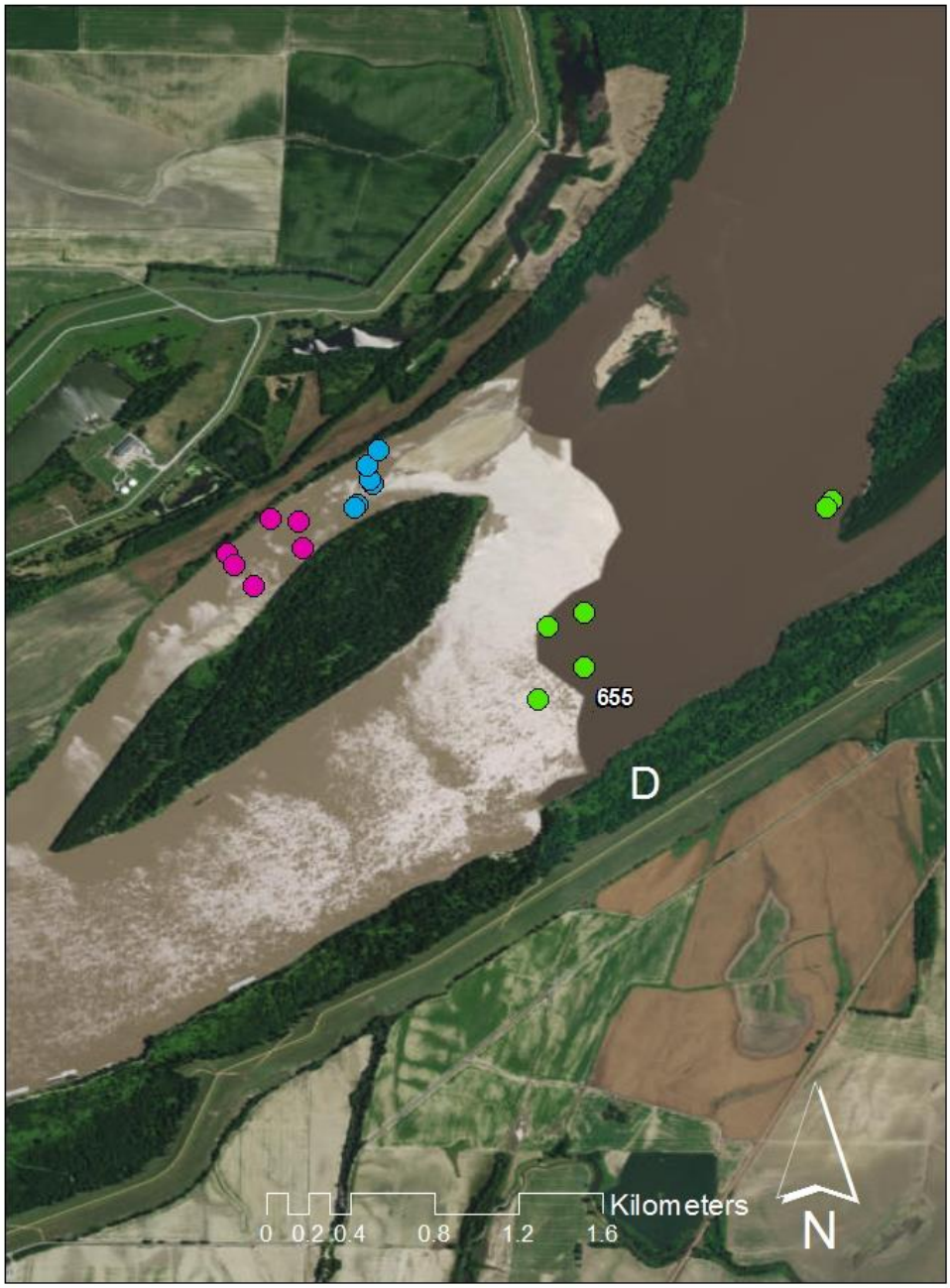
Map B. Mississippi River at Walnut Bend, near Tunica, MS (RM 676-680).



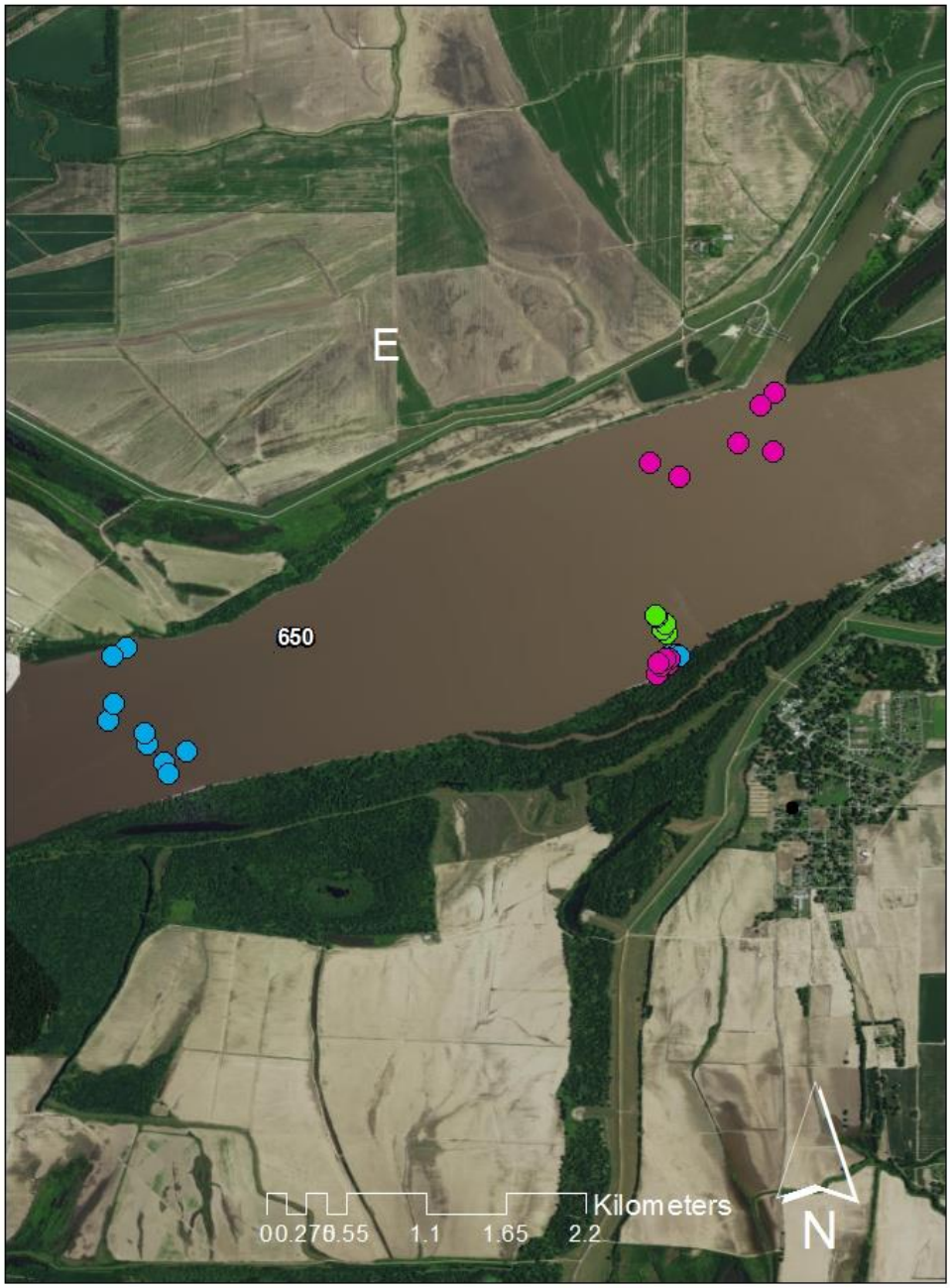
Map C. Mississippi River at Prairie Point, near Helena, AR (RM 661-668).



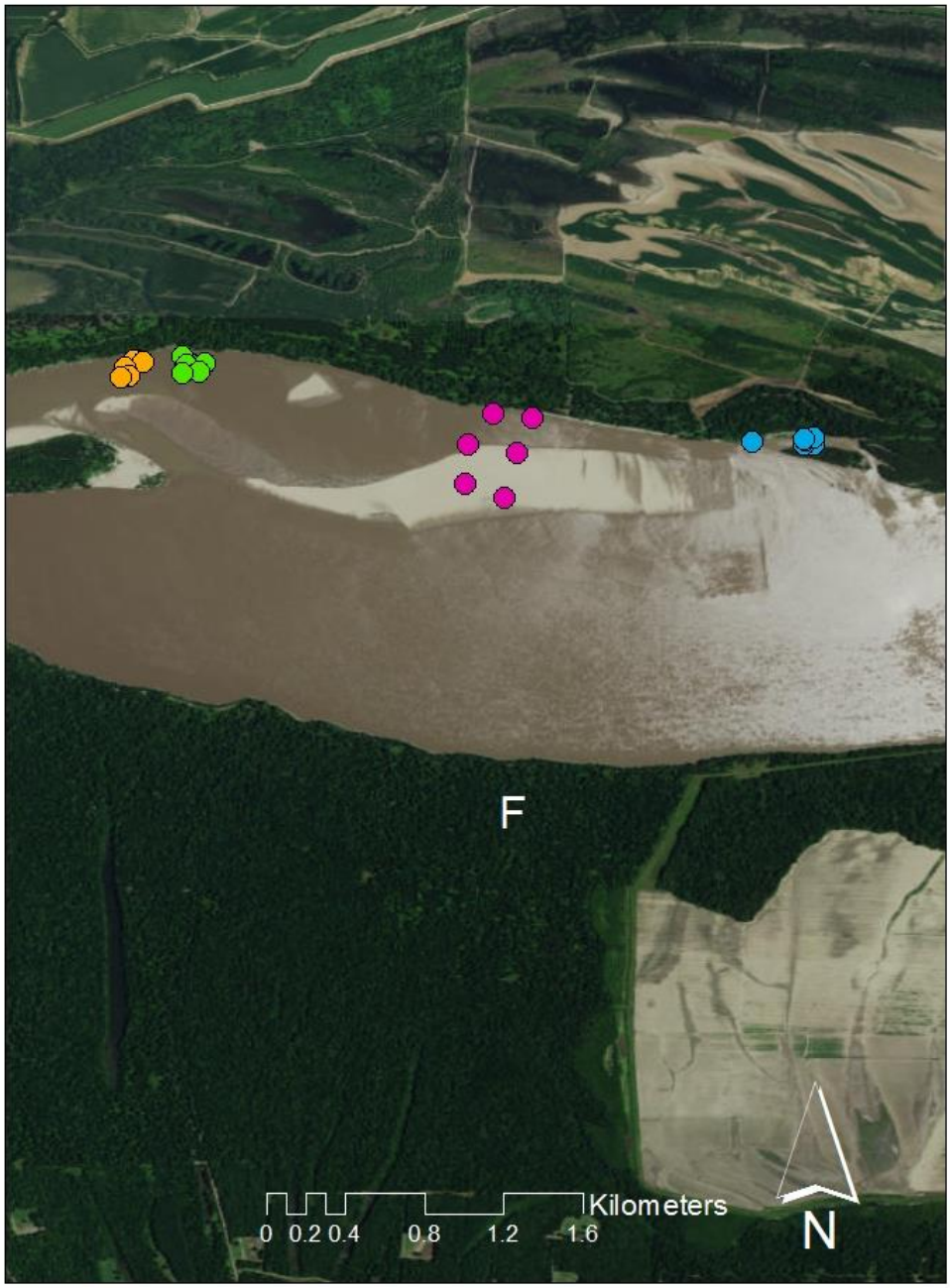
Map D. Mississippi River at Montezuma Towhead, near Helena, AR (RM 652-659).



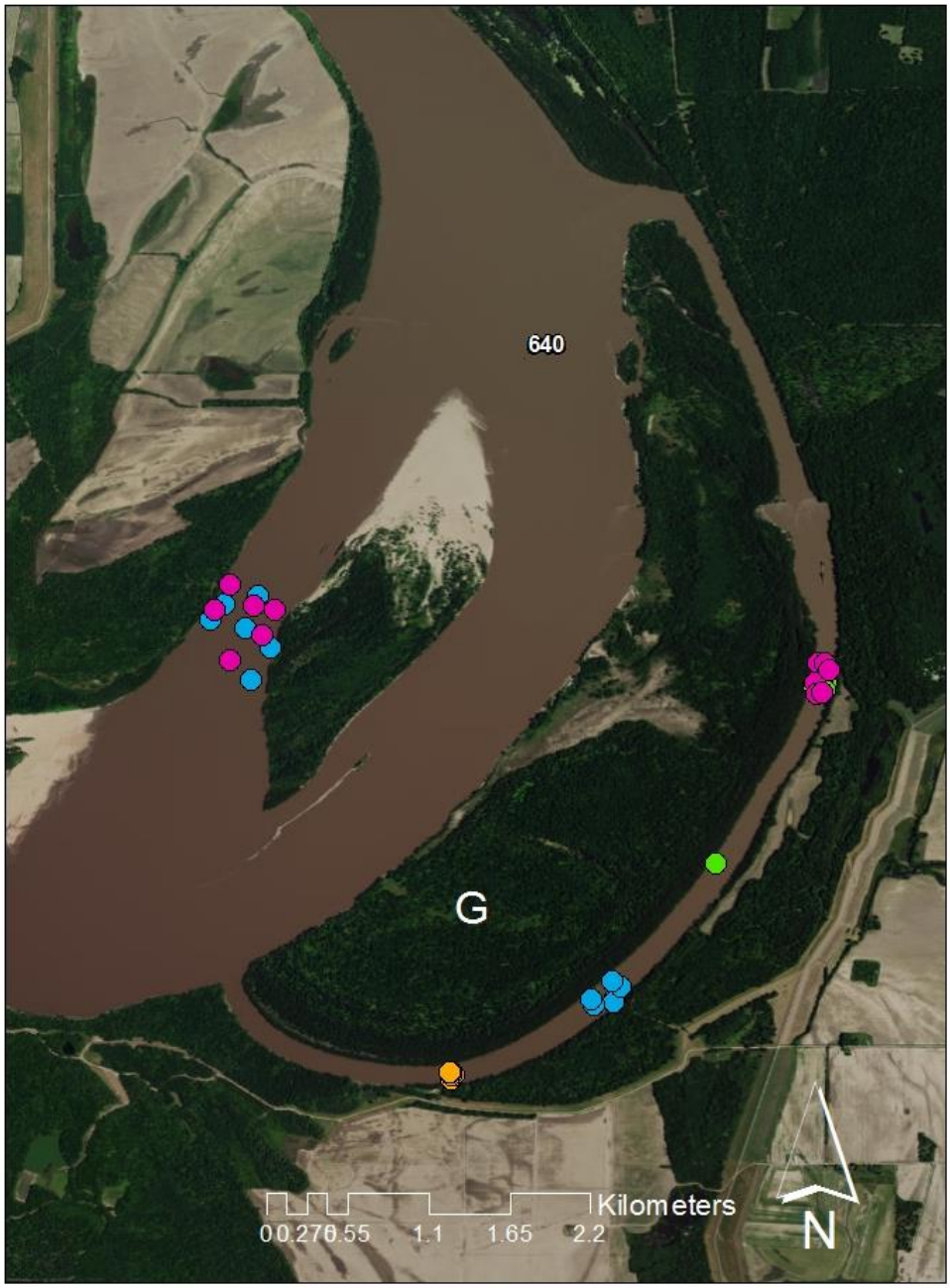
Map E. Mississippi River at Friars Point, MS (RM 649-653).



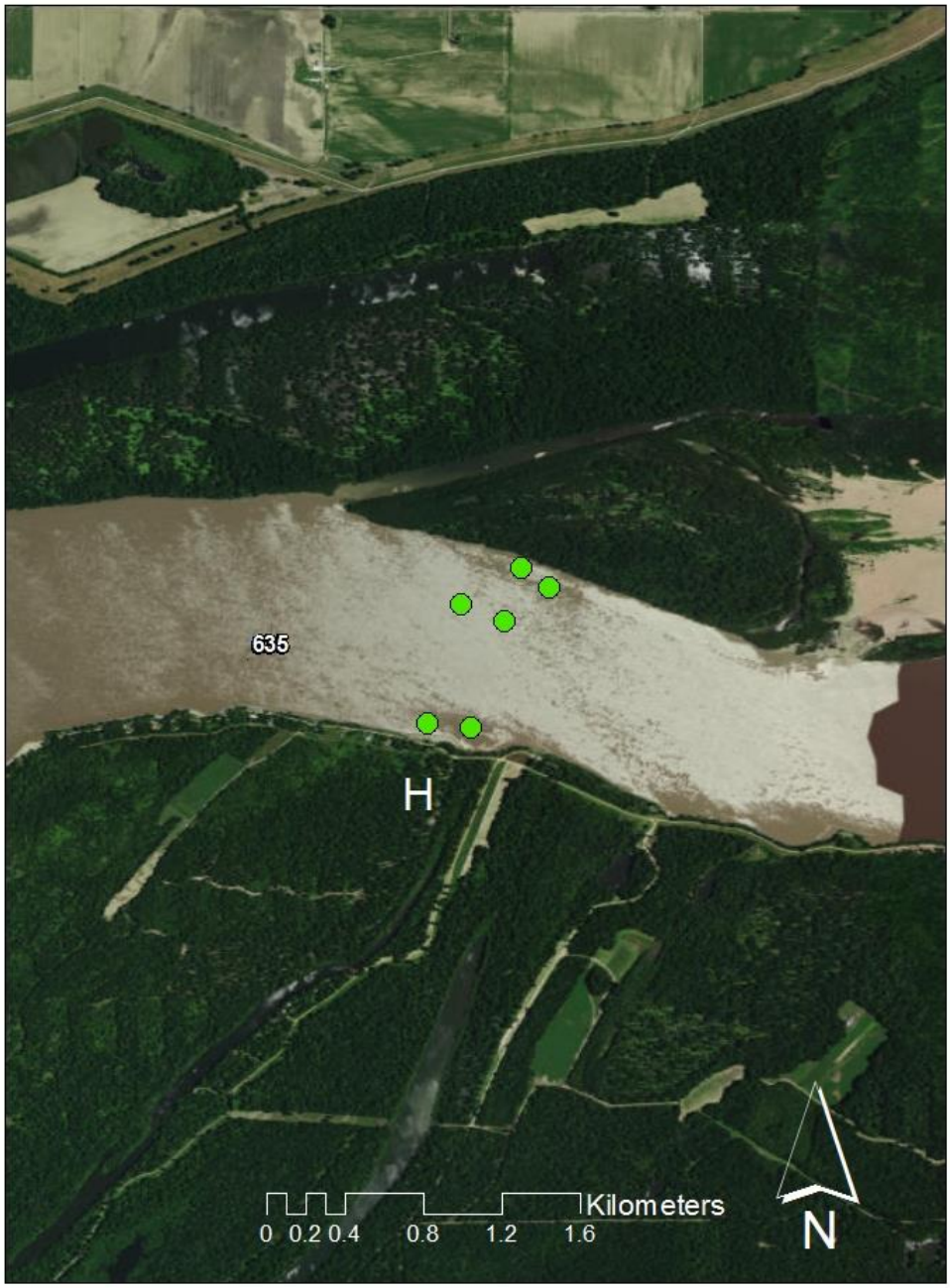
Map F. Mississippi River at Kangaroo Point, near Friars Point, MS (RM 644-649).



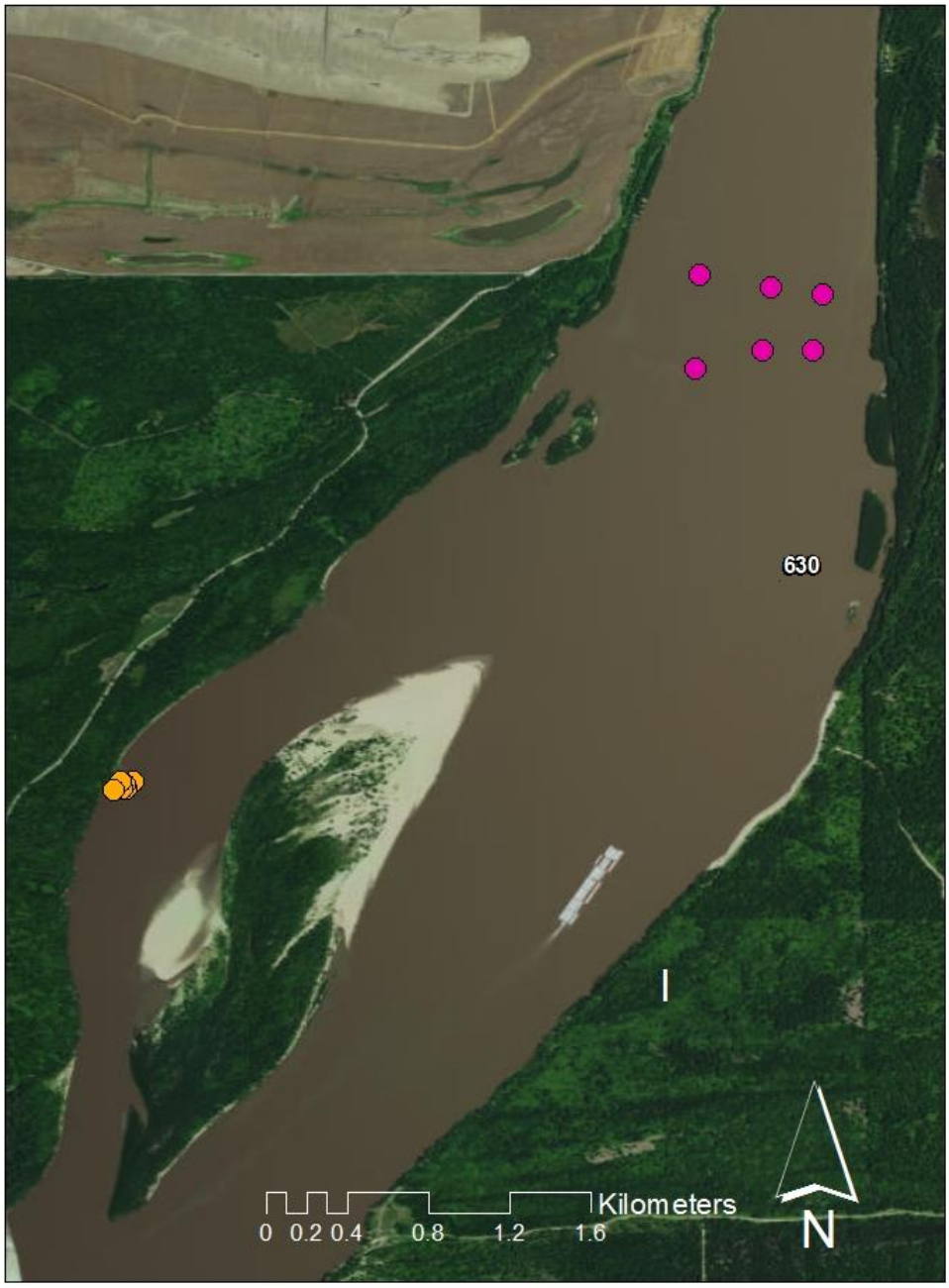
Map G. Mississippi River at Island 62-63, near Clarksdale, MS (RM 636-642).



Map H. Mississippi River near Clarksdale, MS (RM 634-638).

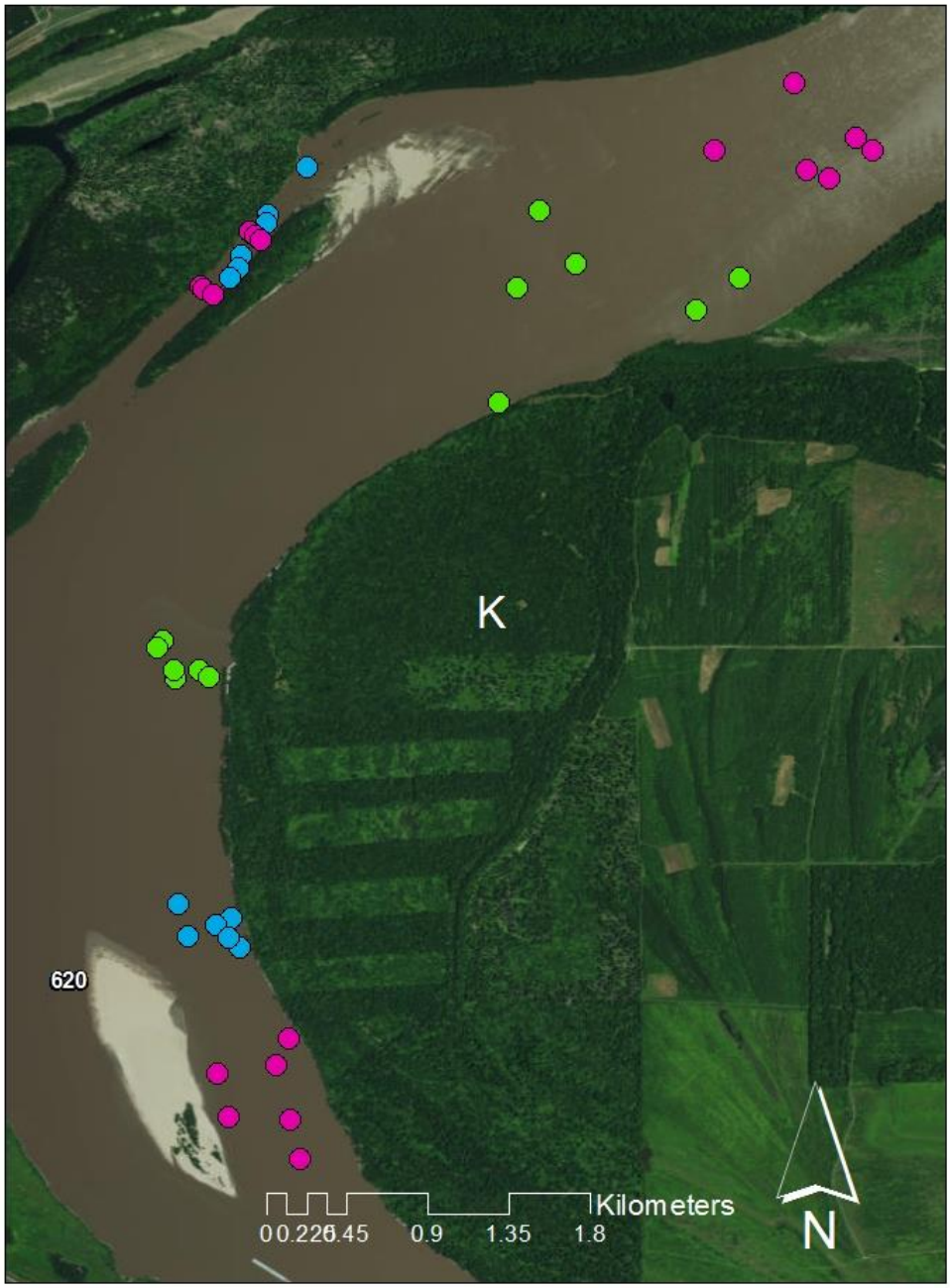


Map I. Mississippi River at Island 64, near Clarksdale, MS (RM 626-633).



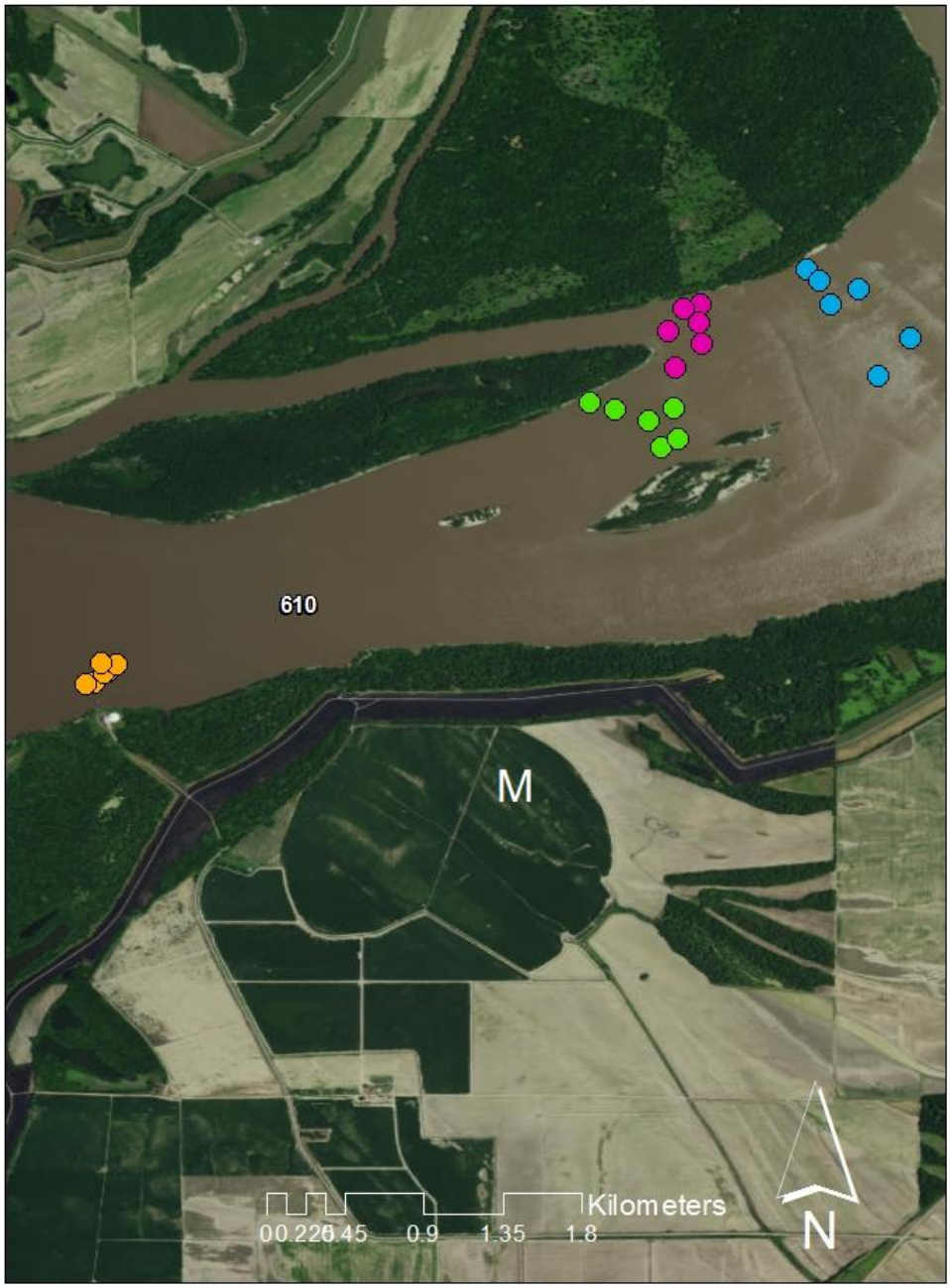
Map J. Mississippi River at Sunflower Dikes, near Clarksdale, MS (RM 625-627).

Map K. Mississippi River at Ludlow, near Ferguson, AR (620-624).

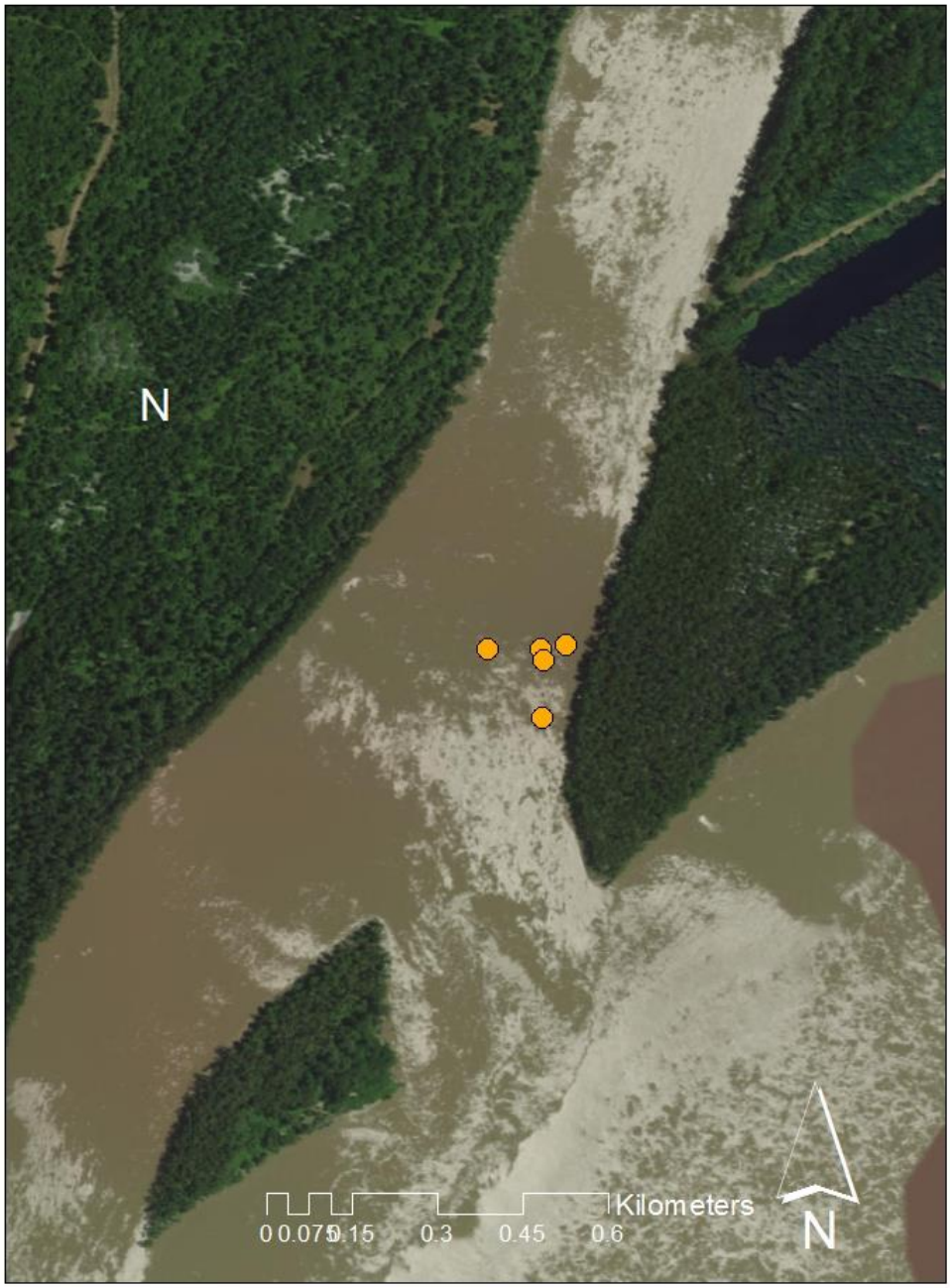


Map L. Mississippi River at Cessions, near Francis, MS (RM 614-617).

Map M. Mississippi River at Knowlton, near Dennis Landing, MS (RM 609-612).



Map N. Old White River channel at mouth of Mississippi River (RM 591).



APPENDIX B: CHAPTER III MACROINVERTEBRATE DATA

Table 1. Macroinvertebrate taxa collected from Glory Hole (Burkes Hunting Club, Clarksdale, MS).

Glory Hole	Sampling Dates							
Taxa Collected	Oct-14	Feb-15	Mar-15	May-15	Jun-15	Aug-15	Sep-15	Aug-16
Insecta								
Diptera								
Chironominae			3	3		1		1
Orthocladiinae								1
Tanypodinae			3	3		3		2
Chironomidae undetermined	3							
Probezzia								1
Ceratopogonidae	3		3	2		3		1
Chaoborus				1		3		1
Ephemeroptera								
Hexagenia	1							
Odonata								
Somatochlora			1					
Arachnida								
Hydracarina	1		1			1		1
Crustacea								
Cladocera								1
Copepoda						1		
Cyclopoida								1
Isopoda				1				
Mysidaceae	1							
Mollusca								
Gastropoda						1		
Hydrobiidae								1
Physidae								2
Planorbidae								2
Veneroida								
Sphaeriidae								2
Annelida								
Hirudinea								
Glossiphoniidae								1
Hirudinea	1							
Oligochaeta	3		3	3		3		
Lumbriculidae								1
Polychaeta								1
Nematoda								1

Table 2. Macroinvertebrate taxa collected from Graveyard Bluehole (Burkes Hunting Club, Clarksdale, MS).

Graveyard Bluehole – Map X	Sampling Dates							
Taxa Collected	Oct-14	Feb-15	Mar-15	May-15	Jun-15	Aug-15	Sep-15	Aug-16
Insecta								
Coleoptera								
Dubiraphia								1
Diptera								
Chironominae			3	1		1		1
Tanypodinae			3	1		2		1
Tanytarsini								1
Zavreliella								1
Chironomidae undetermined	3			1				1
Probezzia								1
Chaoborus	3		3	3		3		3
Arachnida								
Araneae								1
Crustacea								
Copepoda	2		2			3		1
Cyclopoida								2
Mollusca								
Gastropoda								
Ancylidae								1
Hydrobiidae								1
Physidae								1
Planorbidae								1
Veneroida								
Sphaeriidae								1
Annelida								
Hirudinea						1		
Oligochaeta	3		3	3		3		2
Nematoda				1				

Table 3. Macroinvertebrate taxa collected from Jim Samples Lake (Burkes Hunting Club, Clarksdale, MS).

Jim Samples Lake – Map X	Sampling Dates							
Taxa Collected	Oct-14	Feb-15	Mar-15	May-15	Jun-15	Aug-15	Sep-15	Aug-16
Insecta								
Diptera								
Chironominae			3	2				
Tanypodinae			3					
Chironomidae undetermined	3			1				
Ceratopogonidae	1		2					
Chaoborus	3		3	3		3		1
Crustacea								
Copepoda								
Copepoda	3		3	1		3		
Cyclopoida								1
Ostracoda								
Ostracoda	1		2	1				
Mollusca								
Gastropoda								
Planorbidae								1
Annelida								
Oligochaeta								
Oligochaeta	3		3	2		3		1

Table 4. Macroinvertebrate taxa collected from McWilliams Lake (Burkes Hunting Club, Clarksdale, MS).

McWilliams Lake	Sampling Dates							
Taxa Collected	Oct-14	Feb-15	Mar-15	May-15	Jun-15	Aug-15	Sep-15	Aug-16
Insecta								
Coleoptera								
Dubiraphia								2
Diptera								
Chironominae			3	1		1		2
Tanypodinae			3	1		3		2
Tanytarsini								1
Tanytarsus								1
Zavreliella								1
Chironomidae undetermined	3			2				
Ceratopogonidae	3		3	3		1		2
Chaoborus	1		3	3		3		1
Hemiptera								
Corixidae	1							
Odonata								
Neurocordulia								1
Trichoptera								
Hydroptilidae								1
Oecetis	1							1
Leptoceridae Undetermined								1
Arachnida								
Araneae								1
Hydracarina	1					2		1
Crustacea								
Cladocera								1
Sididae								1
Copepoda						3		
Cyclopoida								1
Ostracoda			1					
Mollusca								
Gastropoda								
Planorbidae								1
Unionoida								
Unionidae								1
Veneroida								
Sphaeriidae								2
Annelida								
Hirudinea	1							1
Oligochaeta	3		3	3		3		

McWilliams Lake Cont.	Sampling Dates							
Taxa Collected	Oct-14	Feb-15	Mar-15	May-15	Jun-15	Aug-15	Sep-15	Aug-16
Polychaeta								2

Table 5. Macroinvertebrate taxa collected from Old River Chute (Burkes Hunting Club, Clarksdale, MS).

Old River Chute	Sampling Dates							
Taxa Collected	Oct-14	Feb-15	Mar-15	May-15	Jun-15	Aug-15	Sep-15	Aug-16
Insecta								
Coleoptera								
Dubiraphia								1
Collembola								
Isotomidae								1
Diptera								
Chironominae				3	3		2	1
Chironomini								1
Tanypodinae				3	3		2	2
Tanytarsus								1
Zavreliella							71	1
Chironomidae undetermined		3						
Probezzia								1
Ceratopogonidae		3		3	3		2	1
Chaoborus		2		2	3		3	1
Stratiomyidae				1				
Ephemeroptera								
Hexagenia		1						
Hemiptera								
Corixidae		1						
Trichoptera								
Oecetis				1				
Orthotrichia		1						
Arachnida								
Arachnida								
Hydracarina		2					1	1
Crustacea								
Copepoda				1	1		3	
Cyclopoida								2
Harpacticoida								2
Mysidaceae		1						
Mollusca								
Gastropoda								
Gastropoda				1				
Physidae								1
Annelida								
Hirudinea							1	
Oligochaeta		3		3	3		3	1
Polychaeta								1

Old River Chute Cont.	Sampling Dates							
Taxa Collected	Oct-14	Feb-15	Mar-15	May-15	Jun-15	Aug-15	Sep-15	Aug-16
Nematoda				2				

Table 6. Macroinvertebrate taxa collected from Desoto Lake near Clarksdale, MS.

Desoto Lake	Sampling Dates							
Taxa Collected	Oct-14	Feb-15	Mar-15	May-15	Jun-15	Aug-15	Sep-15	Aug-16
Insecta								
Coleoptera								
Berosus								1
Diptera								
Chironominae			2	2				4
Tanypodinae			1	3				4
Zavreliella								1
Chironomidae undetermined	4		2					
Probezzia								1
Ceratopogonidae	1		1	1				1
Chaoborus	2		2	1				3
Stratiomyidae	1							
Hemiptera								
Corixidae								1
Arachnida								
Araneae								1
Hydracarina	1							1
Crustacea								
Cladocera								1
Copepoda	1		1	1				
Cyclopoida								2
Isopoda	1							
Ostracoda			1	2				
Mollusca								
Gastropoda				1				
Lymnaeidae								1
Physidae								2
Planorbidae								2
Annelida								
Hirudinea								
Glossiphoniidae								1
Oligochaeta	6		5	6				
Lumbriculidae								1
Nematoda			1	1				

Table 7. Macroinvertebrate taxa collected from Island 63 Secondary Channel near Clarksdale, MS.

Island 63 Secondary Channel (Chapter 3)	Sampling Dates							
Taxa Collected	Oct-14	Feb-15	Mar-15	May-15	Jun-15	Aug-15	Sep-15	Aug-16
Insecta								
Coleoptera								
Stenelmis				1				
Diptera								
Chironominae				8				4
Chironomini								1
Orthocladiinae				2				
Tanypodinae				3				1
Chironomidae undetermined								6
Ceratopogonidae				1				
Simuliidae				2				
Brachycera				1				1
Ephemeroptera								
Baetidae								2
Caenis								1
Cercobrachys (nr.) *serpentis*								5
Hexagenia				2				1
Maccaffertium								1
Heptageniidae Undetermined				1				1
Pentagenia								6
Pseudiron				2				
Tortopsis								2
Ephemeroptera Undetermined								1
Odonata								
Dromogomphus				4				3
Stylurus								1
Trichoptera								
Hydropsyche				1				5
Potamyia				3				6
Hydropsychidae Undetermined				1				1
Nectopsyche				1				3
Leptoceridae Undetermined								
Arachnida								
Araneae								1
Crustacea								
Amphipoda								

Island 63 Secondary Channel Cont.	Sampling Dates							
Taxa Collected	Oct-14	Feb-15	Mar-15	May-15	Jun-15	Aug-15	Sep-15	Aug-16
Apocorophium								3
Gammaridae Undetermined								1
Gammarus								3
Copepoda				1				
Decapoda								
Palaemonidae				5				
Isopoda				1				
Lirceus								5
Mollusca								
Gastropoda								
Physidae								1
Veneroida								
Corbicula								4
Sphaeriidae								2
Annelida								
Hirudinea				1				
Glossiphoniidae								1
Oligochaeta				7				3

Table 8. Macroinvertebrate taxa collected from Island 64 Secondary Channel near Mellwood, AR.

Island 64 Secondary Channel	Sampling Dates							
Taxa Collected	Oct-14	Feb-15	Mar-15	May-15	Jun-15	Aug-15	Sep-15	Aug-16
Insecta								
Diptera								
Chironominae				9				3
Robackia								3
Orthocladiinae				6				
Tanypodinae				3				2
Chironomidae undetermined								2
Chaoborus				2				
Tipulidae								1
Diptera undetermined				1				1
Ephemeroptera								
Cercobrachys (nr.) serpentis								3
Ephemeroptera Undetermined								1
Heptageniidae Undetermined				1				
Hexagenia				2				3
Pentagenia								1
Pseudiron				3				
Odonata								
Dromogomphus								2
Trichoptera								
Hydropsyche								1
Hydropsychidae Undetermined								1
Leptoceridae Undetermined								1
Polycentropus								
Potamyia								
Arachnida								
Hydracarina				1				
Crustacea								
Amphipoda								
Gammarus								1
Cladocera				2				
Copepoda				7				
Decapoda								
Palaemonidae				5				
Isopoda				1				1
Asellidae								2

Island 64 Secondary Channel Cont.	Sampling Dates							
Taxa Collected	Oct-14	Feb-15	Mar-15	May-15	Jun-15	Aug-15	Sep-15	Aug-16
Mollusca								
Gastropoda				1				
Veneroida								
Corbicula								3
Sphaeriidae								4
Veneroida								1
Annelida								
Oligochaeta				4				2

Table 9. Macroinvertebrate taxa collected from Mellwood Lake near Mellwood, AR.

Mellwood Lake	Sampling Dates							
Taxa Collected	Oct-14	Feb-15	Mar-15	May-15	Jun-15	Aug-15	Sep-15	Aug-16
Insecta								
Coleoptera								
Staphylinidae								1
Diptera								
Chironominae		6			6		4	5
Cryptochironomus								1
Tanypodinae		6			2		4	3
Chironomidae undetermined		3						1
Ceratopogonidae		2					1	1
Chaoborus		1			5		9	4
Brachycera								1
Ephemeroptera								
Cercobrachys (nr.) *serpentis*								1
Hemiptera								
Corixidae								1
Odonata								
Libellulidae							1	
Trichoptera								
Hydropsyche								1
Oecetis								1
Arachnida								
Hydracarina		1						1
Crustacea								
Copepoda		3					1	
Cyclopoida								3
Harpacticoida								1
Ostracoda		1					1	
Mollusca								
Gastropoda		1					1	1
Hydrobiidae								2
Lymnaeidae								1
Physidae								4
Planorbidae								5
Veneroida								
Sphaeriidae								5
Annelida								
Oligochaeta		7			9		9	2
Lumbriculidae								1
Polychaeta								1

Mellwood Lake Cont.	Sampling Dates							
Taxa Collected	Oct-14	Feb-15	Mar-15	May-15	Jun-15	Aug-15	Sep-15	Aug-16
Nematoda		1						2

Table 10. Macroinvertebrate taxa collected from Borrow Pit A near Elaine, AR.

Borrow Pit A	Sampling Dates							
Taxa Collected	Oct-14	Feb-15	Mar-15	May-15	Jun-15	Aug-15	Sep-15	Aug-16
Insecta								
Diptera								
Chironominae		2			3		3	1
Chironomini								1
Tanypodinae		2			3		3	3
Chironomidae undetermined		1						
Ceratopogonidae		3			2		3	3
Chaoborus		3			2		2	1
Trichoptera								
Leptocerus					2			
Arachnida								
Araneae								1
Crustacea								
Copepoda		2			2		2	
Harpacticoida								3
Ostracoda		2						2
Mollusca								
Gastropoda								
Hydrobiidae								1
Veneroida								
Sphaeriidae							2	
Annelida								
Hirudinea					2			
Oligochaeta		3			2		3	1
Naididae								1

Table 11. Macroinvertebrate taxa collected from Borrow Pit B near Elaine, AR.

Borrow Pit B	Sampling Dates							
Taxa Collected	Oct-14	Feb-15	Mar-15	May-15	Jun-15	Aug-15	Sep-15	Aug-16
Insecta								
Coleoptera								
Peltodytes					1			
Diptera								
Chironominae		2			3		2	3
Tanypodinae		2			3		3	3
Chironomidae undetermined		1						
Ceratopogonidae		1			2		3	2
Chaoborus		2			2		2	
Arachnida								
Arachnida								
Hydracarina		1						
Crustacea								
Copepoda		1			1		1	
Harpacticoida								1
Ostracoda								
Ostracoda		2						
Mollusca								
Gastropoda								
Physidae								2
Planorbidae								2
Veneroida								
Sphaeriidae							1	2
Sphaeromias								1
Nematoda		1						
Annelida								
Oligochaeta		3			3		3	

Table 12. Macroinvertebrate taxa collected from Sunflower Dikes Secondary Channel near Alligator, MS.

Sunflower Dikes Secondary Channel (Chapter 3)	Sampling Dates							
Taxa Collected	Oct-14	Feb-15	Mar-15	May-15	Jun-15	Aug-15	Sep-15	Aug-16
Insecta								
Diptera								
Chironominae								3
Robackia								1
Tanypodinae								3
Probezzia								1
Ephemeroptera								
Cercobrachys (nr.) *serpentis*								1
Heptageniidae Undetermined								1
Hexagenia								3
Pentagenia								1
Odonata								
Dromogomphus								2
Trichoptera								
Nectopsyche								1
Crustacea								
Isopoda								
Asellidae								2
Lirceus								1
Annelida								
Oligochaeta								1

APPENDIX C: CHAPTER IV MACROINVERTEBRATE DATA

Table 1. Macroinvertebrate taxa collected from Cessions Secondary Channel near Francis, MS (Map L).

Cessions Secondary Channel	Sampling Dates			
Taxa Collected	Jun-14	Nov-14	Jun-15	Oct-15
Insecta				
Diptera				
Chernovskiia				39
Lopescladius				1
Paratendipes				21
Rheosmittia				1
Robackia				1
Trichoptera				
Hydropsychidae				1
Mollusca				
Gastropoda				2
Veneroida				
Sphaeriidae				12

Table 2. Macroinvertebrate taxa collected from Friars Point Secondary Channel near Friars Point, MS (Map E).

Friars Point Secondary Channel	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Insecta				
Collembola				
Hypogasturidae	1			
Diptera				
Chernovskiia		1		
Chironomus	379	1	10	
Coelotanypus			1	
Cryptochironomus	8	5	14	
Dolichopodidae			1	
Harnischia		1		
Polypedilum	4		43	
Procladius	2			
Rheotanytarsus		1	1	
Stictochironomus			1	
Chironomidae undetermined	5	1	3	
Ceratopogonidae			1	
Brachycera		1		
Ephemeroptera				
Cercobrachys (nr.) *serpentis*			3	
Hexagenia	1	4	1	
Pentagenia			2	
Pseudiron	1			
Raptoheptagenia	1			
Spinadis			1	
Baetidae			3	
Heptageniidae			2	
Ephemeroidea undetermined			1	
Odonata				
Dromogomphus		1	3	
Trichoptera	13	8	25	
Hydropsyche			5	
Potamyia	13	5	20	
Hydropsychidae		3		
Crustacea				
Amphipoda		4		
Apocorophium	5	39	1	
Gammaridae	3	13	32	

Friars Point Secondary Channel Cont.	**Sampling Dates**			
	Jun-14	Nov-14	Jun-15	Oct-15
Hyallela			1	
Mollusca				
Gastropoda			2	
Veneroida				
Corbicula		2		
Sphaeriidae			7	
Annelida				
Hirudinea			1	
Oligochaeta	30	60	123	

Table 3. Macroinvertebrate taxa collected from Hurricane Point/Chevrons near Dennis Landing, MS (Map M).

Hurricane Point/Chevrons at Dennis Landing	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Insecta				
Diptera				
Chironomus				8
Coelotanypus				2
Harnischia				15
Paratendipes				1
Polypedilum				3
Procladius				1
Robackia				1
Stictochironomus				1
Brachycera				1
Ephemeroptera				
Hexagenia				65
Pentagenia				1
Tortopsis				3
Odonata				
Dromogomphus				2
Trichoptera				
Potamyia				1
Crustacea				
Amphipoda				
Gammaridae				1
Mysidacea				2
Mollusca				5
Veneroida				5
Corbicula				1
Sphaeriidae				4
Annelida				
Oligochaeta				10

Table 4. Macroinvertebrate taxa collected from Island 62 Secondary Channel near Clarksdale, MS (Map G).

Island 62 Secondary Channel	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Insecta				
Diptera				
Chernovskiia	2		1	
Cryptochironomus	3			
Lipiniella	4			
Polypedilum	9			
Procladius			1	
Robackia	3		1	
Chironomidae undetermined	3		1	
Ephemeroptera				
Caenis	1			
Isonychia	1			
Pentagenia	2			
Pseudiron	2			
Raptoheptagenia	3			
Baetidae	1			
Trichoptera				
Cheumatopsyche	4			
Potamyia	239			
Hydropsychidae			1	
Nectopsyche	2			
Crustacea				
Amphipoda				
Apocorophium	13			
Gammaridae	9			
Cladocera				
Daphnia	1			
Mollusca				
Veneroida				
Corbicula	5			
Annelida				
Oligochaeta			1	

Table 5. Macroinvertebrate taxa collected from Island 63 Secondary Channel near Clarksdale, MS (Map G).

Island 63 Secondary Channel	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Insecta				
Coleoptera		1		
Stenelmis		1		
Collembola		1		
Diptera				
Ablabesmyia	2			
Axarus	2			
Chernovskiia	3		8	
Chironomus			1	26
Coelotanypus		1		2
Cryptochironomus	2	14		36
Harnischia				3
Lipiniella	2			
Lopescladius	10			
Microchironomus				2
Microspectra				2
Paralauterborniella				1
Paratendipes		7	4	36
Polypedilum	73	6		7
Polypedilum sp. B	2			
Pseudochironomus				1
Robackia	4	6		
Saetheria	2			
Simulium	15			
Stenochironomus		1	2	
Stictochironomus		2		
Tribelos	2			
Chironomidae undetermined	6	1		2
Atrichopogon				1
Ephemeroptera				
Hexagenia		3		16
Pentagenia		2		3
Tortopsis	20			
Baetidae	7	2		
Heptageniidae	8	5	1	
Odonata				

Island 63 Secondary Channel Cont.	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Didymops		1		
Dromogomphus		5		11
Gomphidae		1		7
Trichoptera				
Cheumatopsyche	2			
Hydropsyche	199	10	1	
Nectopsyche		4		
Potamyia	671	17		1
Undetermined Trichoptera				1
Crustacea				
Amphipoda	33	80	1	2
Apocorophium	6	72	1	2
Gammaridae	27	8		
Copepoda		1	1	1
Copepoda		1	1	1
Decapoda	1			
Palaemonetes	1			
Isopoda	1		1	
Asellidae			1	
Isopoda	1			
Mollusca				
Gastropoda			1	
Veneroida				
Corbicula	13	31		6
Sphaeriidae			3	27
Undet Bivalve	2			
Annelida				
Oligochaeta	3	109	16	8

Table 6. Macroinvertebrate taxa collected from Island 64 Secondary Channel near Clarksdale, MS (Map I).

Island 64 Secondary Channel	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Insecta				
Diptera				
Chironomus				552
Parachironomus				2
Stenochironomus				1
Crustacea				
Mysidacea				2
Mollusca				
Gastropoda				1
Veneroida				2
Annelida				
Oligochaeta				8

Table 7. Macroinvertebrate taxa collected from Island 67 Secondary Channel near Ferguson, AR (Map K).

Island 67 Secondary Channel	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Insecta				
Diptera				
Chernovskiia		1	4	
Chironomus		2		
Coelotanypus		11		
Cryptochironomus		26		
Demicryptochironomus		1		
Lipiniella	1			
Lopescladius	4		2	
Polypedilum	1	1		
Rheosmittia	3			
Robackia	18		4	
Chironomidae undetermined	4		1	
Ephemeroptera				
Hexagenia		15		
Odonata				
Dromogomphus		4		
Trichoptera				
Hydropsyche		1		
Potamyia	1	2	1	
Nectopsyche		1		
Crustacea				
Amphipoda		5	1	
Apocorophium		4	1	
Gammaridae		1		
Copepoda			2	
Mollusca				
Veneroida	6	5		
Corbicula	6	5		
Annelida				
Oligochaeta		117	4	

Table 8. Macroinvertebrate taxa collected from Kangaroo Point Secondary Channel near Friars Point, MS (Map F).

Kangaroo Point Secondary Channel	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Insecta				
Diptera				
Ablabesmyia				4
Chernovskiia			2	
Chironomus	1	17	68	251
Coelotanypus		22	1	8
Cryptochironomus		2	1	3
Lipiniella	4			
Lopescladius			2	
Microchironomus				2
Parachironomus			1	
Paratendipes		1		
Polypedilum	9		1	1
Procladius			15	2
Tanypus				1
Xestochironomus	1			
Chironomidae undetermined	1		3	2
Chaoborus		1		8
Simulium	2			
Ephemeroptera				
Hexagenia		10	2	9
Pentagenia	1		1	
Tortopsis	2			
Odonata				
Dromogomphus		2		
Gomphidae		1		
Plecoptera				
Perlesta	2			
Trichoptera				
Cheumatopsyche	1			
Hydropsyche	16			
Potamyia	2			
Crustacea				
Amphipoda				
Gammaridae	10	1	1	
Cladocera				1
Copepoda			3	3

Kangaroo Point Secondary Channel Cont.	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Mysidacea		4		
Mollusca				
Veneroida		4		
Corbicula		3		
Undet Bivalve		1		
Annelida				
Oligochaeta	2	14	73	29

Table 9. Macroinvertebrate taxa collected from Knowlton Secondary Channel near Dennis Landing, MS (Map M).

Knowlton Secondary Channel	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Insecta				
Coleoptera			2	
Copotomus			1	
Stenelmis			1	
Diptera				
Chernovskiia	4		2	
Chironomus	3	2		
Coelotanypus		22		
Cryptochironomus	1	61	1	
Demicryptochironomus			1	
Harnischia	3			
Lopescladius	2		1	
Paralauterborniella	1			
Paratendipes	2			
Polypedilum	1		1	
Pseudochironomus		22		
Robackia	7		4	
Saetheria	10			
Tanypus	1			
Chironomidae undetermined	3	1	1	
Ephemeroptera	3	15		
Hexagenia		12		
Neoephemera	2			
Pentagenia		2		
Pseudiron	1			
Tortopsis		1		
Odonata				
Dromogomphus	1	1		
Trichoptera				
Potamyia			4	
Crustacea				
Amphipoda				
Apocorophium		3	1	
Gammaridae			6	
Mysidacea		2		
Mollusca				
Veneroida				

Knowlton Secondary Channel Cont.	**Sampling Dates**			
	Jun-14	Nov-14	Jun-15	Oct-15
Corbicula	9	1		
Annelida				
Oligochaeta		33	2	

Table 10. Macroinvertebrate taxa collected from Ludlow Secondary Channel near Dennis Landing, MS (Map M).

Ludlow Secondary Channel	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Insecta				
Diptera	179		1	
Chironomus	68			
Cryptochironomus	22			
Harnischia	50			
Lipiniella	16			
Lopescladius			1	
Paralauterborniella	9			
Polypedilum	1			
Robackia	4			
Saetheria	2			
Tanypus	1			
Chironomidae undetermined	6			
Ephemeroptera				
Hexagenia	15			
Neoephemera	1			
Undetermined	1			
Odonata				
Dromogomphus	4			
Trichoptera				
Hydropsyche	1			
Crustacea				
Copepoda			1	
Mollusca				
Veneroida				
Corbicula	5			
Annelida				
Oligochaeta	8		88	

Table 11. Macroinvertebrate taxa collected from the main channel Mississippi River between Tunica and Rosedale, MS (Maps A-C, E, H-I, K).

Main Channel	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Insecta				
Coleoptera			2	
Copotomus			1	
Stenelmis			1	
Diptera				
Chernovskiia	5	12	19	50
Chironomus	11	2		3
Coelotanypus	1			1
Cryptochironomus	16	1	2	
Cryptotendipes	1			
Harnischia	10			
Lopescladius	10		4	1
Parachironomus		1		
Paratendipes		5		
Polypedilum	4		1	
Procladius	3			1
Rheosmittia	3		2	1
Robackia	29	22	12	51
Chironomidae undetermined	1	1		1
Ceratopogonidae	1			
Chaoborus	1			
Ephemeroptera				
Hexagenia		1		
Isonychia				1
Pentagenia	1	2		
Pseudiron	1			
Raptoheptagenia			1	
Baetidae			1	
Caenidae		1		
Odonata				
Dromogomphus	3			
Plecoptera		1		
Perlodidae		1		
Trichoptera				
Ceratopsyche			1	
Hydropsyche	1	2	6	2
Potamyia	3	1	4	28

Main Channel Cont.	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Hydropsychidae		1	2	
Undetermined Trichoptera		1		
Crustacea				
Amphipoda			1	
Apocorophium	1	11	1	19
Gammaridae	1		2	1
Cladocera				7
Daphnia	1			
Copepoda	1	2	1	1
Mysidacea				1
Mollusca				
Gastropoda		2		3
Rhodacmea				1
Veneroida				
Corbicula		73		
Sphaeriidae			3	28
Undet Bivalve		9		
Annelida				
Oligochaeta	107	21	1	15

Table 12. Macroinvertebrate taxa collected from Montezuma Secondary Channel near Helena, AR (Map D).

Montezuma Secondary Channel	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Insecta				
Diptera				
Chironomus	6			
Lipiniella	1			
Polypedilum	1			
Robackia	1			
Chironomidae undetermined	3			
Crustacea				
Copepoda			1	
Annelida				
Oligochaeta	1		3	

Table 13. Macroinvertebrate taxa collected from Old White River Channel near Rosedale, MS (Map N).

Old White River Channel	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Annelida				
Oligochaeta				3
Arachnida				1
Insecta				
Diptera				
Chernovskiia				67
Chironomus				1
Demicryptochironomus				2
Harnischia genus C				2
Paratendipes				1
Robackia				59
Ephemeroptera				
Hexagenia				6
Odonata				
Gomphidae				1
Mollusca				
Veneroida				
Sphaeriidae				8

Table 14. Macroinvertebrate taxa collected from Prairie Point Secondary Channel near Helena, AR (Map C).

Prairie Point Secondary Channel	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Insecta				
Diptera				
Ablabesmyia				10
Chironomus		22		394
Coelotanypus		3		134
Cryptochironomus		2		16
Harnischia		9		
Lipiniella	4			
Lopescladius			1	
Microchironomus				62
Parachironomus				1
Polypedilum	6			7
Procladius				45
Robackia	11		1	
Tanypus				7
Chironomidae undetermined	1			34
Culicoides		1		
Ceratopogonidae				1
Chaoborus				2
Ephemeroptera				
Hexagenia		3		57
Stenonema	1			
Trichoptera				
Cheumatopsyche	2			
Hydropsyche		1	1	
Potamyia	7		2	
Crustacea				
Amphipoda				
Gammaridae		1		
Cladocera				31
Daphnia	1			
Copepoda				2
Mysidacea		1		5
Mollusca				
Veneroida				
Corbicula	2			
Sphaeriidae			1	

Prairie Point Secondary Channel Cont.	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Undet Bivalve	1			
Annelida				
Oligochaeta	2	13		9

Table 15. Macroinvertebrate taxa collected from Sunflower Dikes Secondary Channel near Clarksdale, MS (Map J).

Sunflower Dikes Secondary Channel	Sampling Dates			
	Jun-14	Nov-14	Jun-15	Oct-15
Insecta				
Diptera				
Chironomus				16
Coelotanypus				4
Cryptochironomus				1
Harnischia				33
Paracladopelma				1
Paralauterborniella				4
Polypedilum				5
Procladius				1
Chironomidae undetermined				2
Ephemeroptera				
Hexagenia				56
Pentagenia				15
Odonata				
Dromogomphus				4
Trichoptera				
Potamyia				2
Crustacea				
Amphipoda				
Gammaridae				2
Copepoda				1
Mollusca				
Veneroida				
Sphaeriidae				1
Annelida				
Oligochaeta				51
Haplotaxidae				1
Tubificidae				20
Polychaeta				1

APPENDIX D: CHAPTER VI MACROINVERTEBRATE RECORDS/GIS FILE

Table D.1. Distributional data for *Cercobrachys serpentis* (Ephemeroptera: Caenidae) from published literature, major collections, and this study. Stage: L = larva, A = adult, M = adult male, F = adult female, I = subimago.

State	County	Location	Date	No./ Stage	Collect-ors	Latitude	Longitude	Comments	Collection	Citation
ID	Owyhee	Snake River at Payette	7/30/1998	1 L	B Alcorn, R Piston	43.6686	-116.9901		PERC	Sun and McCafferty 2008
ID	Payette	Snake River at Payette	8/7/1965		GF Edmunds	44.091	-116.9568		PERC	Sun and McCafferty 2008
MS	Coahoma	Island 63 Secondary Channel, lower reach	8/19/2015	1 L	ABH, WTS, BRL, JAC, KJK	34.2673	-90.75467	*near C. serpentis; This study	ERDC	
MS	Coahoma	Mississippi River, Friars Point Secondary Channel	6/24/2015	1 L	ABH, WTS, BRL, JAC	34.3735	-90.6473	*near C. serpentis; This study	ERDC	
MS	Coahoma	Mississippi River, Friars Point Secondary Channel	6/24/2015	1 L	ABH, WTS, BRL, JAC	34.374	-90.64711	*near C. serpentis; This study	ERDC	
MS	Coahoma	Mississippi River, Island 63 Secondary Channel, middle reach	8/19/2015	2 L	ABH, WTS, BRL, JAC, KJK	34.2924	-90.72002	*near C. serpentis; This study	ERDC	

MS	Coahoma	Mississippi River, Island 63 Secondary Channel, upper reach	8/19/2015	1 L	ABH, WTS, BRL, JAC, KJK	34.3176	-90.73137	*near C. serpentis; This study	ERDC	
MS	Coahoma	Sunflower Dikes Secondary Channel	8/20/2015	1 L	ABH, WTS, BRL, JAC	34.1708	-90.89156	*near C. serpentis; This study	ERDC	
MS	Coahoma	Sunflower Dikes Secondary Channel	8/20/2015	3 L	ABH, WTS, BRL, JAC	34.1715	-90.89221	*near C. serpentis; This study	ERDC	
MT	Rosebud	Tongue River, Ashland	7/17/1990	4 L	DL Gustafson	45.6178	-106.2855		PERC	Sun and McCafferty 2008
NE	Furnas	Republican River, Oxford River channel	8/11/1982	L, A	AVP	40.2462	-99.71132			McCafferty et al. 2001
NE	Pawnee	N Fork Big Nemaha River, 1 mi E Table Rock, St Rd 4	8/12/1997	L	THK	40.1834	-96.07461			McCafferty et al. 2001
NE	Sheridan	Niobrara River, Gordon	7/11/1984	L		42.6685	-102.1566			McCafferty et al. 2001
NE	Sheridan	Niobrara River, Gordon	8/21/1984	L		42.6685	-102.1566			McCafferty et al. 2001

NE	Sheridan	Niobrara River, S Gordon	7/27/1984		HRL	42.7319	-102.1788			McCafferty et al. 2001
UT		Snake River in Utah						* probably reported in error		Lillie and Hilsenhoff 1993
WI	Grant	Woodman, Big Green River Boat Landing Hwy 133		52 L		43.0916	-90.80102	5/31-9/1, mature L, 6/13-9/1 emergence		Lillie and Hilsenhoff 1992
WI	La Crosse	1 km W Council Bay at US-53 Canoe Launch, Black River	6/19/2012	1 L	RE DeWalt	44.0614	-91.29141		INHS	
WY	Sweetwater	Black's Fork River at I-80, W Green River City	8/2/1969	1 L	AV Provonsha	41.5282	-109.461		PERC	Sun and McCafferty 2011

Table D.2. Distributional data for *Raptoheptagenia cruentata* (Ephemeroptera: Heptageniidae) from published literature, major collections, and this study. Stage: L = larva, A = adult, M = adult male, F = adult female, I = subimago.

State	County	Location	Date	No./ Stage	Collect-ors	Latitude	Longitude	Comments	Collection	Citation
AR	Phillips	Island 62 Secondary Channel	6/11/2014	3 L	ABH, WTS, BRL, JAC	34.29314	-90.7549	*This study		
IA	Fremont	Missouri River (under Hwy 2 bridge) @ Nebraska City	5/25/1994	4 L	BCP	40.67143	-95.83		BCP/USGS Collection	
IA	Pottawatt-amie	Missouri River				41.27234	-95.9089	*Locality for MO River @ Pottawattamie County		McCafferty et al. 2003
IA	Scott	Davenport	1929			41.52056	-90.5761			McCafferty et al. 2003
IL	Adams	Quincy Mississippi River	7/13/1937	1 M	C.O. Mohr, B.D. Burks	39.93363	-91.4181		INHS	
IL	Adams	Quincy Mississippi River	6/7/1939	1 M	B.D. Burks, G.T. Riegel	39.93363	-91.4181		INHS	
IL	Adams	Quincy Mississippi River	6/8/1939	1 M	B.D. Burks, G.T. Riegel	39.93363	-91.4181		INHS	
IL	Lee	Dixon Rock River	6/27/1935	1 M	D.M. DeLong, H.H. Ross	41.84557	-89.4845		INHS	

IL	Marion	Patoka	7/19/1945	1 M	H.H. Ross, M.W. Sanderson	38.7558	-89.0951		INHS	
IL	Pike	Lights at Motel Pike, W side of Pittsfield	6/10/1997	1 M, 1 F	M.A. Harris, D.L. Adolphson	39.6041	-90.8277		INHS	
IL	Rock Island	Rock Island Rock River	6/7/1937	1 M	B.D. Burks, G.T. Riegel	41.51346	-90.5829		INHS	
IL	Union	Anna	7/22/1938	1 M	B.D. Burks, Boesel	37.46028	-89.2469		INHS	
IL	Wabash	Mt. Carmel Wabash River	5/25/1942	1 L	C.O. Mohr, B.D. Burks	38.404	-87.7516		INHS	
IL	Wabash	Mt. Carmel Wabash River	5/28/1942	1 L	C.O. Mohr, B.D. Burks	38.404	-87.7516		INHS	
IL	Whiteside	Prophetstown	7/24/1947	1 M	M.W. Sanderson, B.D. Burks	41.671	-89.936		INHS	
IL	Winnebago	Rockton Rock River	6/25/1947	1 M	B.D. Burks	42.45036	-89.0723		INHS	
IN	Jefferson	Ohio River	5/26/1981	1 L		38.73741	-85.4041			Jacobus and Webb 2013
IN	Martin	East Fork White River at Hindostan Falls Public Fishing Site	6/20/1974	1 A	AV Provonsha, L Dersch	38.62395	-86.8536			Jacobus and Webb 2013

IN	Martin	East Fork White River at Hindostan Falls Public Fishing Site	7/2/1974	1 M	AV Provonsha, Lick	38.62395	-86.8536			Jacobus and Webb 2013
IN	Martin	East Fork White River at Hindostan Falls Public Fishing Site	7/2/1974	1 M, 2 F	AV Provonsha, L Dersch, M Lick	38.62395	-86.8536			Jacobus and Webb 2013
IN	Martin	East Fork White River at Hindostan Falls Public Fishing Site	6/8/1978	1 M, 2 F	M Minno, D Bloodgood	38.62395	-86.8536			Jacobus and Webb 2013
IN	Martin	East Fork White River at Hindostan Falls Public Fishing Site	7/15/1982	1 M, 1 F	AV Provonsha, V VanAllen	38.62395	-86.8536			Jacobus and Webb 2013
IN	Parke	Raccoon Lake	6/24/1973		HR Lawson	39.75237	-87.074			Jacobus and Webb 2013
IN	Tippecanoe	Wabash River at West Lafayette	7/13/1973	1 A	Provonsha	40.42403	-86.8976			Jacobus and Webb 2013
IN	Tippecanoe	Wabash River at West Lafayette	6/18/1974	3 A	Provonsha	40.42403	-86.8976			Jacobus and Webb 2013
MN	Sibley	Minnesota River, drift net	6/30/1974	1 L	C.M. Haynes	44.53	-93.9013			Waltz et al. 1998

MO	Gasconade	Missouri River @ Hermann, MO	6/18/1997	2 M	BCP	38.70778	-91.4378		BCP/USGS	
MO	Jackson	Kansas City				39.11549	-94.5792	*Locality for MO River @ Kansas City		Poulton et al. 2003
MO	Platte	Missouri River @ Parkville, MO	7/24/1997	1 M	BCP	39.19113	-94.7687		BCP/USGS	
MS	Coahoma	Friars Point Secondary Channel	6/12/2014	1 L	ABH, WTS, BRL, JAC	34.37409	-90.6462	*This study		
MS	Coahoma	Mississippi River Main Channel	6/24/2015	1 L	ABH, WTS, BRL, JAC	34.38725	-90.6426	*This study		
MT	Carter	Little Missouri River; Sec 12, T 6S, R 62E	7/17/1996	1 L		45.0327	-104.425			Waltz et al. 1998
MT	Cluster	Powder River	8/11/1976	2 L	G. Romero	46.39457	-105.321			Waltz et al. 1998
MT	Cluster	Powder River	11/11/1976	1 L	G. Romero	46.39457	-105.321			Waltz et al. 1998
MT		Powder River Site 1	7/11/2005	8 L		45.01504	-105.906			Stagliano 2006
MT		Powder River Site 1 at wy border	7/11/2005	13 L		45.01504	-105.906			Stagliano 2006
MT		Powder River Site 2 at Dry Creek	7/11/2005	14 L		45.03771	-105.881			Stagliano 2006
MT		Powder River Site 2 at Dry Creek	7/11/2005	9 L		45.03771	-105.881			Stagliano 2006
MT		Powder River Site 3 at Jenkins Reach	7/11/2005	9 L		45.10619	-105.838			Stagliano 2006

		Wide								
MT		Powder River Site 3 at Jenkins Targeted Riffle	7/11/2005	13 L		45.10619	-105.838			Stagliano 2006
MT		Powder River Site 5 at Rough Creek Targeted Riffle	7/12/2005	7 L		45.34667	-105.533			Stagliano 2006
MT		Powder River Site 6 at Buttermilk Creek	7/12/2005	5 L		45.2256	-105.691			Stagliano 2006
ND	Billings	Little Missouri River at Ash Coulee	6/15/2004			47.12167	-103.553			Guenther and McCafferty 2005
ND	Bowman	Little Missouri River, 22 km S Marmarth E Camp Crook Rd	6/15/2004			46.16556	-103.887			Guenther and McCafferty 2005
ND	Burleigh	Missouri River	6/21/2003			46.67194	-100.668			Guenther and McCafferty 2005
ND	Dunn	Little Missouri River at Crosby Creek	6/16/2004			47.57683	-103.072			Guenther and McCafferty 2005

ND	McKenzie	Little Missouri River at Beicegel Creek	8/7/2004			47.45333	-103.629			Guenther and McCafferty 2005
ND	McKenzie	Little Missouri River at CCC Camp	6/15/2004			47.58611	-103.279			Guenther and McCafferty 2005
ND	McKenzie	Little Missouri River at Cedar Creek	6/16/2004			47.52083	-103.617			Guenther and McCafferty 2005
ND	McKenzie	Yellowstone River at SR 200, N bridge	8/7/2004			47.86361	-103.964			Guenther and McCafferty 2005
ND	Morton	Missouri River	6/21/2003			46.67194	-100.668			Guenther and McCafferty 2005
ND	West Slope	Little Missouri River at Pretty Butte	6/14/2004			46.38389	-103.941			Guenther and McCafferty 2005
ND	West Slope	Little Missouri River at VVV Crossing	6/15/2004			46.39667	-103.926			Guenther and McCafferty 2005
NE	Douglas	Missouri River, Dodge Park, Omaha	6/10/1997		THK	41.25398	-95.9223			McCafferty et al. 2001
NE	Lancaster	Lincoln	1935		Traver	40.83804	-96.6918			McCafferty et al. 2001
NE	Nemaha	Auburn at light	6/27/1997			40.39637	-95.8324			McCafferty et al. 2001

NE	Nemaha	Peru St Coll at light	6/22/1995		THK	40.47473	-95.7316			McCafferty et al. 2001
OH	Brown	Ohio River, near Aberdeen	6/1/1976	2 L		38.66495	-83.7772	as Anepeorus sp.		Beckett 1977
TN	Shelby			1 A		35.16135	-90.0608	*Locality for MS River @ Memphis		Berner 1977

Table D.3. Distributional data for *Spinadis simplex* (Ephemeroptera: Heptageniidae) from published literature, major collections, and this study. Stage: L = larva, A = adult, M = adult male, F = adult female, I = subimago.

State	County	Location	Date	No./ Stage	Collect-ors	Latitude	Longitude	Comments	Collect-ion	Citation
AR	Chicot	Mississippi River, 1.61 km below Greenville, MS	Jul-78		C Bingham	33.3345	-91.1649	*Same record as below, most likely		McCafferty 2009
AR	Chicot	Mississippi River, RM 529	Jun-78	1 L	Sanders and Bingham	33.3345	-91.1649			Sanders and Bingham 1980
AR	Jefferson	Arkansas River near Pine Bluff, T.6S, R.7W, S.7	5/15/1980		Thomas Lager	34.27407	-91.9643			Lager 1985
GA	Fulton	Chattahoochee River at Atlanta Georgia		1 M	PW Fattig	33.8176	-84.4803			Needham et al. 1935
GA	Toombs	Altamaha River at US Hwy 1	6/5/1973	4 L	B. Wallace	31.93968	-82.3548			Edmunds and Jensen 1974
IA								as Anepeorus simplex (Lager 1985)		Lager 1985

IL		Wabash River		22 A 3 L		38.39958	-87.7577	*State only record/ Locality for Mt. Carmel, IL		Burks 1953
IN	Vigo	Wabash River, Public Service Indiana's Wabash Generating Station, Terre Haute	6/14/1973	4 L	Mancini, Gammoa, Carlson	39.47484	-87.4204			Mancini et al. 1976
IN		White River				38.516	-87.471	*locality approx-imate		Edmunds and Jensen 1974
MS	Coahoma	Friars Point Secondary Channel	6/24/2015	1 L	ABH, WTS, BRL, JAC, KJK	34.37297	-90.6476	*This study		
MS	Washing-ton	Mississippi River, 1.61 km below Greenville, MS			C Bingham	33.3345	-91.1649			McCafferty 2009
WI	Iowa		1/1/1978			43.15968	-90.1271	*County only record		Lillie and Hilsenhoff 1992
WI	Richland	Orion	1975 and 1978		Flowers and Hilsenhoff	43.20196	-90.4281			Lillie and Hilsenhoff 1992

WI	Richland	Port Andrew	May-88	1		43.20602	-90.5725			Lillie and Hilsenhoff 1992
WI	Richland	Wisconsin River	6/23/1973	6 L	WL Hilsenhoff W Flowers	43.20568	-90.4164			Edmunds and Jensen 1974
WI	Richland		1/1/1978			43.20568	-90.4164	*County only record		Lillie and Hilsenhoff 1992
WI		Wisconsin River	6/26/1974	1		43.46608	-89.4435	*Locality approx-imate		Flowers and Hilsenhoff 1987

Table D.4. Distributional data for *Pseudiron centralis* (Ephemeroptera: Pseudironidae) from published literature, major collections, and this study. Stage: L = larva, A = adult, M = adult male, F = adult female, I = subimago, EX = exuvae.

State	County	Location	Date	No./ Stage	Collectors	Latitude	Longitude	Comm-ents	Collect-ion	Citation
AL	Dallas			1 A		32.400199	-87.014946			Berner 1977
AL	Dallas					32.33957	-87.129029	*County only record		Kondratieff and Harris 1986
Alberta		Milk R at Writing, Stone Prov. Pk	7/21/1982	1 L, 1 A	UA	55.092778	-110.870354			Pescador 1985
Alberta		Sand River nr mouth	7/25/1977	1 A	FSCA	55.092778	-110.870354			Pescador 1985
Alberta		Sand River nr mouth	6/15-23/1982	1 L, 1 A	UA	55.092778	-110.870354			Pescador 1985
Alberta			1985		Pescador	55.615841	-114.606791			McCafferty and Randolph 1998
AR	Lee	Mississippi River, Mhoon Landing	05/02/06	12	ERDC	34.751390	-90.461120	In sturgeon diet	ERDC	
AR	Lee	MS River Mhoon Bend	5/10/2007	4 L	ERDC	34.73798	-90.46111		ERDC	
CA	Sacramento	Sherwood Harbor, Sacramento River, west of Sacramento	5/14/2003		McCafferty and Meyer	38.595231	-121.506039		PERC	McCafferty and Meyer 2007

CA	Yolo	Sacramento River, west of Sacramento	5/14/2003		McCafferty and Meyer	38.600614	-121.5149		PERC	McCafferty and Meyer 2007
CO	Otero	Arkansas River at Fowler	6/12/1974	L		38.135923	-104.023867		CSUC	McCafferty et al. 1993
FL	Calhoun	Chipola River Hwy 274 Cross Chipola	4/12/1983	2	FDEP	30.55116	-85.1714		FDEP	
FL	Escambia	Perdido River Hwy 184 Br Musgogee		1	FDEP	30.60277	-87.4025		FDEP	
FL	Gasden	Mosquito Circle Hwy 269 ref for Chatta-hoochee STP FYI	4/28/2003	1	FDEP	30.687778	-84.843333		FDEP	
FL	Okaloosa	Blackwater R at Bryant bridge 3 mi NW Holt	2/20/1971	1 L	FAMU	30.79843	86.768721			Pescador 1985
FL	Okaloosa	Blackwater R, FAMU Biol. Sta. 4 1/4 mi NW Holt	1/31/1971	2 L	FAMU	30.79843	86.768721			Pescador 1985
FL	Okaloosa	Blackwater R, FAMU Biol. Sta. 4 1/4 mi NW Holt	2/22/1971	3 L	FAMU	30.79843	86.768721			Pescador 1985

FL	Okaloosa	Blackwater R, FAMU Biol. Sta. 4 1/4 mi NW Holt	3/13/1971	1 A	FAMU	30.79843	86.768721			Pescador 1985
FL	Okaloosa	Blackwater R, FAMU Biol. Sta. 4 1/4 mi NW Holt	4/23/1971	1 A	FAMU	30.79843	86.768721			Pescador 1985
FL	Okaloosa	Blackwater R, FAMU Biol. Sta. 4 1/4 mi NW Holt	4/8/1972	3 L	FAMU	30.79843	86.768721			Pescador 1985
FL	Okaloosa	Blackwater R, FAMU Biol. Sta. 4 1/4 mi NW Holt	5/1/1974	1 A	FAMU	30.79843	86.768721			Pescador 1985
FL	Okaloosa	Blackwater R, FAMU Biol. Sta. 4 1/4 mi NW Holt	5/1/1975	1 A	FAMU	30.79843	86.768721			Pescador 1985
FL	Okaloosa	Blackwater R, FAMU Biol. Sta. 4 1/4 mi NW Holt	4/15/1976	1 L, 1 A	FAMU	30.79843	86.768721			Pescador 1985
FL	Okaloosa	Blackwater R, FAMU Biol. Sta. 4 1/4 mi NW Holt	4/16/1977	3 L	FAMU	30.79843	86.768721			Pescador 1985
FL	Okaloosa	Blackwater R, FAMU Biol. Sta. 4 1/4 mi NW Holt	5/3/1977	1 A	FAMU	30.79843	86.768721			Pescador 1985

FL	Okaloosa	Blackwater R, FAMU Biol. Sta. 4 1/4 mi NW Holt	5/9/1977	1 L, 1 A	FAMU	30.79843	86.768721			Pescador 1985
FL	Okaloosa	Blackwater R, FAMU Biol. Sta. 4 1/4 mi NW Holt	4/22/1978	3 L	FAMU	30.79843	86.768721			Pescador 1985
FL	Okaloosa	Blackwater R, FAMU Biol. Sta. 4 1/4 mi NW Holt	4/3/1979	1 A	FAMU	30.79843	86.768721			Pescador 1985
FL	Okaloosa	Blackwater R, Kennedy bridge 6 mi W Blackman	4/23/1974	1 L, 1 A	FAMU	30.79843	86.768721			Pescador 1985
FL	Okaloosa	Blackwater R, Peaden bridge 4 1/2 mi NW Cannon Town	4/28/1976	1 L, 1 A	FAMU	30.79843	86.768721			Pescador 1985
FL	Okaloosa	Blackwater R, Peaden bridge 4 1/2 mi NW Cannon Town	5/11/1984	1 A	FAMU	30.79843	86.768721			Pescador 1985
FL	Okaloosa	Blackwater River at Hwy 4	2/15/2005	2	FDEP	30.833395	-86.733732		FDEP	
FL	Okaloosa	Yellow River Hwy 90 W of Crestive	11/1/1974	2	FDEP	30.75278	-86.62741		FDEP	
FL	Santa Rosa	Blackwater R, Riley Landing, 3 mi NW Holt	4/24/1971	1 L	FAMU	30.717623	-86.811299			Pescador 1985
FL	Santa Rosa	Blackwater R, Riley Landing, 3 mi NW Holt	4/7/1984	1 A	FAMU	30.717623	-86.811299			Pescador 1985

FL	Santa Rosa			1 L		30.834456	-86.830568			Berner 1977
FL	Walton	At light 1/2 mi W Defuniak Springs Hwy 90	4/20/1960	1 A	FSCA	30.722273	-86.115217			Pescador 1985
FL	Walton			1 A		30.668893	-86.106437			Berner 1977
FL										Peters and Jones 1973
GA										Needham et al. 1935
IA	Muscatine	Fairport	1935		Traver	41.435504	-90.90441			McCafferty et al. 2003
IA	Polk	"County 77"	1985		Pescador	41.69956	-93.622667	*County only record		McCafferty et al. 2004
IA		County 77	7/3/1939	1 A	INHS			Possibly same as "Polk Co." specimen		Pescador 1985
IL	Adams	Quincy	7/6/1939	1 M	Mohr and Riegel	39.933064	-91.413325			Burks 1953
IL	Adams	Quincy at light	6/8/1939	1 M	Burks and Reigel	39.933064	-91.413325			Burks 1953
IL	Clinton	Centralia, at light	6/17/1947	1 A	INHS	38.544312	-89.104575			Pescador 1985
IL	Lee	Prophetstown dredging sandy bottom of Rock R 15 yds from bank	5/21/1925	1 L	INHS	41.814687	-89.582939			Pescador 1985

IL	Lee	Rock Falls, Rock R. at light	6/26/1967	1 A	INHS	41.78414	-89.692047			Pescador 1985
IL	Lee	Dixon, at light	6/26/1947	1 A	INHS	41.844327	-89.481915			Pescador 1985
IL	Mercer	Keithsburg at light on MS River	Jun-32	1 F		41.100149	-90.945561			Burks 1953
IL	Wabash	Mt Carmel, at light	6/18/1947	1 A	INHS	38.404101	-87.75152			Pescador 1985
IL	Whiteside	Prophetstown, Rock R	6/26/1967	1 A	INHS	41.672724	-89.928805			Pescador 1985
IL	Whiteside	Prophetstown, sweeping vegetation on bank of Rock River	6/26/1947	1 F, 2 M	BD Burks	41.674001	-89.935777			Burks 1953
IL	Whiteside	Rock Falls at light	6/26/1947	1 M	BD Burks	41.783064	-89.693337			Burks 1953
IL	Winnebago	Rockford	6/2/1944	1 M	HS Dybas	42.262955	-89.093337			Burks 1953
IL	Winnebago	Rockford	6/2/1949	1 A	INHS	42.266558	-89.094916			Pescador 1985
IN	Pike	White R nr Petersburg Plant	5/2/1975	1 L	PU	38.511547	-87.289188			Pescador 1985
KS	Douglas	Lawrence	6/26/1930	1 A	CNC	38.934366	-95.289053			Pescador 1985
KS	Saline	New Cambria, Saline River	6/10/1976		Fry & KDHE	38.874891	-97.517043		SEMC	
KS	Saline	Saline R, New Cambria	6/10/1976	1 L	SBSK	38.874799	-97.513139			Pescador 1985
KS	Sedgwick	Arkansas R,	6/6/1975	1 L	SBSK	37.913131	-97.437234			Pescador

		2.8 mi S Bentley								1985
KS	Sedgwick	Bentley, 2.8 mi S, Arkansas River	6/6/1975		Matthies, Scott	37.842254	-97.518726		SEMC	
KS	Washington	Hollenberg, W, Little Blue River	6/13/1975		KB Sunknown	39.980309	-97.003851		SEMC	
LA	Iberville	Mississippi River, White Castle Ferry	05/05/10	1 L	ERDC	30.182220	-91.151520	In sturgeon diet	ERDC	
LA	St. Bernard	Mississippi River, Caernarvon	05/07/09	10 L	ERDC	29.868640	-89.913910	In sturgeon diet	ERDC	
LA	St. Bernard	Mississippi River, Caernarvon	05/07/09	1 L	ERDC	29.868640	-89.913910	In sturgeon diet	ERDC	
Mani-toba			1931		McDunn-ough	54.140686	-97.385764			McCafferty and Randolph 1998
MI	Mason	19 sites on the Pere Marquette River	Oct-90		AGB Primack	43.914057	-86.345433			McCafferty 1992
MI	Mason	19 sites on the Pere Marquette River	May-91		AGB Primack	43.914057	-86.345433			McCafferty 1992
MS	Bolivar	Knowlton Secondary Channel	6/11/2014	1 L	ABH, WTS, BRL, JAC	34.0329	-90.90246	*This study		
MS	Coahoma	Friars Point Secondary Channel	6/12/2014	1 L	ABH, WTS, BRL, JAC	34.3742	90.364642	*This study		

MS	Coahoma	Mississippi River Main Channel	6/12/2014	1 L	ABH, WTS, BRL, JAC	34.50586	-90.57893	*This study		
MS	Coahoma	Mississippi River, downstream of Island 63	05/30/07	1 L	ERDC	34.275720	-90.772580	In sturgeon diet	ERDC	
MS	Leflore	Tallahatchie R at Greenwood	6/6/1956	1 A	FSCA	33.543889	-90.168412			Pescador 1985
MS	Leflore			1 A		33.667246	-90.216403			Berner 1977
MS	Phillips	Island 62 Secondary Channel	6/11/2014	2 L	ABH, WTS, BRL, JAC	34.29114	-90.75568	*This study	ERDC	
MS	Warren	MS River below Vicksburg	6/1/2007	1 L	ERDC	32.3589	-90.99637		ERDC	
MS	Washington	R.M. 515, dike field, coarse sand	5/17/1978	2 L	Sanders and Bingham	33.126927	-91.122441			Sanders and Bingham 1980
MT	Hill	Milk R, above St John's Bridge	2001		D Gustafson	48.601372	-109.945443			McCafferty 2009
ND	McKenzie	Little Missouri River at Cedar Creek	6/16/2004			47.520833	-103.616944			Guenther and McCafferty 2005
NE	Blaine	N Loup R, Co Rd 1	6/13/2000		THK	42.00671	-100.072546			McCafferty et al. 2001
NE	Dundy	Republican River	1981		Decker	40.08977	-101.417974			McCafferty et al. 2001

NE	Hitchcock	Frenchman River, Republican River	1981		Decker	40.2247	-100.825026			McCafferty et al. 2001
NE	Keith	Ogallala at light nr Platte R	6/22/1981	1 A	UU	41.119567	-101.712646			Pescador 1985
NE	Lincoln	S Platte River	1985		Pescador	41.114962	-100.737691			McCafferty et al. 2001
NE	Lincoln	South Platte R at North Platte	7/6/1981	1 A	UU	41.118053	-100.769835			Pescador 1985
NE	Nemaha	Auburn at light	7/8/1995		THK	40.393855	-95.834567			McCafferty et al. 2001
NE	Nemaha	Peru St Coll at light	6/21/1995		THK	40.47737	-95.732023			McCafferty et al. 2001
NE	Platte	Columbus	1952		Hamilton	41.417507	-97.355965			McCafferty et al. 2001
NE	Red Willow	Republican River	1981		Decker	40.219624	-100.474766			McCafferty et al. 2001
NE	Sheridan	Niobrara R St Rd 27	6/15/1984		WPM	42.639204	-102.209878			McCafferty et al. 2001
NE	Thomas	Dismal River, 13.9 mi S Thedford	6/12/2000		THK	41.800332	-100.617068			McCafferty et al. 2001
NE	Valley	N Loup R	6/25/1998		BCK	41.602552	-98.916016			McCafferty et al. 2001
NE	Wheeler	Cedar R, St Rd 70/91, 41/47/00N98/41/53W	6/6/2000		WPM	41.7833	-98.698409			McCafferty et al. 2001

NE		Niobrara River (no county indicated)	1986		McCafferty and Provonsha	42.821618	-99.214199			McCafferty et al. 2001
Ontario		Rainy River	Jul-68	L	RW Griffiths	48.909875	-91.153518			McCafferty and Randolph 1998
Saskat-chewan		Saskatchewan R at Saskatoon	7/8/1970	1 L	FSCA	52.000265	-107.262316			Pescador 1985
Saskat-chewan			1976		Lehmkuhl	49.995083	-105.397099			McCafferty and Randolph 1998
SC	Allendale			1 L		33.054217	-81.428697			Berner 1977
SC	Cherokee	Broad River				35.117198	-81.575372			Unzicker and Carlson 1982
SC	Darlington	Pee Dee River, ca 800 m downstream of Hwy 15/401 bridge near Society Hill	5/18/1999		Smith	34.522882	-79.83104			McCafferty and Meyer 2009
SC	Marlboro	Pee Dee River, ca 800 m downstream of Hwy 15/401 bridge near Society Hill	5/19/1999		Smith	34.522882	-79.83104			McCafferty and Meyer 2008

SD	Todd	Little White R at small unnamed bridge, Crazy Horse Canyon ca 5 km S Iron Shell Bridge 43/12/07N 100/58/02W	5/29/2003		McCafferty et al.	43.201944	-100.96722			Guenther and McCafferty 2008
SD	Tripp	Keya Paha R at US Hwy 183, 2 km N Wewela	5/29/2003		McCafferty et al.	43.02722	-99.78056			Guenther and McCafferty 2008
TN	Shelby	Business District at store windows	6/7/1956		FSCA	35.147377	-90.056355			Pescador 1985
TN	Shelby			1 A		35.145506	-90.061843			Berner 1977
TN	Unicoi			1 A		36.098472	-82.437095			Berner 1977
TX	Jasper	small stream at bridge on Farm Rd. 256, 10 mi SE Colmesneil	5/4/1977	1 L	PU	30.904348	-94.434309			Pescador 1985
UT	Daggett	R.M. 306.5	9/3/1947	1 A	GFE	40.991594	-109.571428			Edmunds and Musser 1960
UT		Green R Hideout Canyon	10/3/1947	1 A	UU	40.90135	-109.612566			Pescador 1985
WI	Columbia	Portage	7/8/1976	L	Donald Samuelson	43.537337	-89.464582			Lillie and Hilsenhoff 1992

WI	Columbia	Wisconsin River	7/1/1976	1 EX	Edmunds, Jenson & Berner	43.466075	-89.443532			Flowers and Hilsenhoff 1978
WI	Grant	Woodman, Big Green River Boat Landing Hwy 133	6/13/1986	1 EX		43.077079	-90.845552			Lillie and Hilsenhoff 1992
WI	Grant	Woodman, Big Green River Boat Landing Hwy 133	6/1/1987	1 L		43.077079	-90.845552			Lillie and Hilsenhoff 1992
WI	Grant	Woodman, Big Green River Boat Landing Hwy 133	5/29-6/9/1987	3 EX		43.077079	-90.845552			Lillie and Hilsenhoff 1992
WI	Grant	Woodman, Big Green River Boat Landing Hwy 133	9/31/1986	1 EX		43.077079	-90.845552			Lillie and Hilsenhoff 1992
WI	Richland	Pine River at Gotham	5/31/1988		Richard A. Lillie and William L. Hilsenhoff	43.222388	-90.302327			Lillie and Hilsenhoff 1992
WY	Sweetwater	Blacks Fort R at Hwy I 80 W Green R	7/17/1968	1 L	UU	41.295023	-109.535132			Pescador 1985
WY	Sweetwater	R.M. 323	7/21/1959	3 L	GFE	41.018337	-109.562474			Edmunds and Musser 1960

Table D.5. Distributional data for *Tortopsis primus* (Ephemeroptera: Polymitarcyidae) from published literature, major collections, and this study. Stage: L = larva, A = adult, M = adult male, F = adult female, I = subimago.

State	County	Location	Date	No./ Stage	Collectors	Latitude	Longitude	Comments	Collect-ion	Citation
AL								*State only record		Burks 1953
AR	Washington		summer 1958	12 M	LO Warren	36.0034	-94.2376	*County only record	FAMU	McCafferty and Provonsha 1978
AR			1975		McCafferty			*State only record		McCafferty 1994
AR								*State only record		Burks 1953
GA								*State only record		Burks 1953
IA	Cherokee	Cherokee	8/28/1953	2 F	HH Ross	42.7468	-95.55017		FAMU	Molineri 2010
IA	Des Moines	Skunk River at Augusta	8/12/1996		WQL	40.7542	-91.2747			McCafferty et al. 2003
IA	Scott	Buffalo	1956		Thew	41.4542	-90.72002			McCafferty et al. 2003
IA	Story	Ames	1959		Hamilton	42.0277	-93.63517			McCafferty et al. 2003
IL	Adams	Quincy	8/10/1889	1 M	CA Hart	39.9337	-91.41442			Burks 1953

IL	Champaign	Urbana	9/20/1909	2 M		40.1135	-88.20335			Burks 1953
IL	Champaign	Urbana	8/13/1943			40.1116	-88.20447	Many adult females taken in a light trap		Burks 1953
IL	Champaign	Urbana	8/23/1943	5 M	HB Petty	40.1135	-88.20335	at light		Burks 1953
IL	Champaign	Urbana	8/16/1965	3 F	J Kingsolver	40.1116	-88.20447	at light	FAMU	Burks 1953
IL	Champaign		8/21/1892	1 M	CA Hart	40.1135	-88.27876	*County only record		Burks 1953
IL	Gallatin	Shawnee-town	10/3/1942	1 M	Frison and Ross	37.7111	-88.18761			Burks 1953
IL	Hardin	Elizabeth-town	7/14/1948	1 M	Mills and Ross	37.4465	-88.30444	at light		Burks 1953
IL	Henderson	Oquawka	8/26/1947	30 M	HH Ross	40.9376	-90.95713			Burks 1953
IL	Jackson	Grand Tower	8/14/1898	73 F	CA Hart	37.63	-89.50564			Burks 1953
IL	Kankakee	Momence	8/16/1938	1 M	Ross and Burks	41.1625	-87.661			Burks 1953
IL	Madison	Alton	8/29/1913	2 M		38.8891	-90.18615			Burks 1953
IL	Mason	Havana	8/10/1889	1 M	CA Hart	40.2999	-90.06611			Burks 1953

IL	Mason	Havana Township, White Oak Creek	8/14/1896	3 M	CA Hart	40.2467	-90.06737			Burks 1953
IL	McLean	Bloomington		10 M	CC Adams	40.4703	-88.99837			Burks 1953
IL								*State only record		Burks 1953
IN	Posey	Wabash River at Old Dam, New Harmony at light	8/12/1974	8 M, 13 F	AV Provonsha and L Dersch	38.131	-87.94125	8 male imagos and 13 female imagos	PERC	McCafferty 1975
KS	Chase	Cotton-wood River at Cotton-wood Falls (sec 29 T19S, R8E)	8/31/1977	A	DG Huggins and SW Hamilton	38.3754	-96.54306	UV light		Liechti 1981
KS	Douglas	Kansas River at Eudora (sec 5, T13S, R21E)	8/3/1976	A	DG Huggins and PM Liechti	38.9502	-95.09453	UV light		Liechti 1981
KS	Douglas	Wakarusa River at US 59 hwy bridge (sec 24, T13S, R19E)	8/7/1978	A		38.9109	-95.26031	UV light		Liechti 1981

KS	Ellsworth	Kanopolis Reservoir outlet (sec 34, T16S, R6W)	8/3/1977	A	S Roth	38.6479	-98.00693	UV light		Liechti 1981
KS	Lyon	Cottonwood River 9 mi W Emporia	6/19/1978	L	MB DuBois and A Slater	38.384	-96.22621			Liechti 1981
KS	Montgomery	Elk River below Elk City Reservoir (sec 9, T32S, R15E)	7/25/1978	A	MB Dubois and FC Gilbert	37.2734	-95.79435	UV light		Liechti 1981
KS	Osborne	Osborne (KU)		A		39.4392	-98.69331			Liechti 1981
KS	Ottawa	Solomon River 1.0 mi W and 1.0 mi S Bennington (sec 14, T12S, R3W)	9/14/1977	A	PM Liechti	39.0155	-97.6041	UV light		Liechti 1981
KS								*State only record		Burks 1953
LA	East Baton Rouge	Comite River	1975		Louton	30.5183	-91.08541			McCafferty et a. 2010

LA	St. Landry	Atchafalaya River	1975		Louton	30.4835	-91.75744			McCafferty et al. 2010
LA	St. Martin	Atchafalaya River	1975		Louton	30.1141	-91.48375			McCafferty et al. 2010
Mani-toba			1941		Ide	50.4227	-99.42483			McCafferty and Randolph 1998
Mani-toba								*State only record		Burks 1953
MO	Cole	Missouri River, S22 T44N R11W at Jefferson City	7/31/1995	A, L	RJ Sarver	38.5761	-92.15417			Sarver and Kondratieff 1997
MO			1975		McCafferty			*State only record		McCafferty 1994
MO								*State only record		Burks 1953
NE	Buffalo	Kearney			Hamilton	40.6782	-99.08695			McCafferty et al. 2001
NE	Dawson	Cozad			Hamilton	40.8461	-99.98748			McCafferty et al. 2001

NE	Madison	Tri-County Canal			Hamilton	42.0332	-97.64379			McCafferty et al. 2001
NE	Nemaha	Missouri River, Peru, aquatic light trap	7/21/1997		THK	40.4775	-95.69817			McCafferty et al. 2001
NE	Richardson	S Fork Big Nemaha River, St Rd 8, 8 mi SW of Humboldt at light	7/23/1997		THK	40.1584	-95.96049			McCafferty et al. 2001
NE	Washington	Fort Calhoun	1975		McCafferty	41.4554	-96.02543			McCafferty et al. 2001
NE	Washington	Fort Calhoun				41.4553	-96.02546			McCafferty 1975
NE								*State only record		Burks 1953
On-tario								*State only record		Burks 1953
Saskat-chewan			1976		Lehmkuhl	50.5122	-107.2295			McCafferty and Randolph 1998
TN								*State only record		Burks 1953

TX			1994		Lugo-Ortiz and McCafferty			*State only record		McCafferty 1994

Table D.6. Distributional data for *Tortopsis puella* (Ephemeroptera: Polymitarcyidae) from published literature, major collections, and this study. Stage: L = larva, A = adult, M = adult male, F = adult female, I = subimago.

State	County	Location	Date	No./ Stage	Collect-ors	Latitude	Longitude	Comments	Collect-ion	Citation
AL	Barbour					31.911166	-85.156967	*County only record		Kondratieff and Harris 1986
AL	Bibb					32.959758	-87.143145	*County only record		Kondratieff and Harris 1986
AL	Dallas					32.295393	-87.094237	*County only record		Kondratieff and Harris 1986
AL	Mobile					30.690735	-88.071286	*County only record		Kondratieff and Harris 1986
AL	Perry					32.66803	-87.239069	*County only record		Kondratieff and Harris 1986
AL		Cahaba River, lower reaches				32.326224	-87.120368	Sand dominated benthic sediments		Graves and Ward 2011
AL										Berner and Pescador 1988
AR	Chicot	Cracraft Dike Field	Jun-78	3 L		33.049294	-91.162061			Mathis et al. 1981

AR	Chicot	Mississippi River, Island 88 Natural Bank	Jun-78	42 L		33.159841	-91.094886			Mathis et al. 1981
AR	Chicot	Mississippi River, Main Channel	Jun-78	1 L		33.079141	-91.169904			Mathis et al. 1981
AR	Chicot	Mississippi River, Seven Oaks Natural Bank	Jun-78	136 L		33.188478	-91.097631			Mathis et al. 1981
AR	Desha	Chicot Landing Dike Field	9/28/1979			33.651585	-91.189705			Beckett et al. 1983
AR	Lee	Mississippi River, Mhoon Landing	2/27/2008	1 L	ERDC	34.727370	-90.476280	In sturgeon diet	ERDC	
AR	Phillips	Mississippi River, Kangaroo Point Secondary Channel	6/12/2014	2 L	ABH, WTS, BRL, JAC	34.37307	-90.70468			
AR		American Cut-Off	6/19/1979			33.252299	-91.092567			Beckett et al. 983
AR		Anconia Natural Bank	6/26/1979	56 L		33.231726	-91.115575			Mathis et al. 1981

AR		Anconia Natural Bank	9/20-28/1979			33.231726	-91.115575			Beckett et al. 1983
FL	Escambia		August	A		30.484118	-87.38346	*County only record		Berner 1977
FL	Liberty	Apalachicola R at Hwy 20, 10-V-1967		10 L	P.H. Carlson	30.436792	-85.002041			Molineri 2008
FL		Choctawhatchee River				30.872917	-85.879204			Berner and Pescador 1988
FL		Only in the NW part of the state from the Apalachicola R westward				30.229374	-85.090671			Berner and Pescador 1988
GA	Bibb	Macon	7/29/1931	1	P.W. Fattig	32.8492	-83.644		INHS	
GA	Bibb	Macon	7/29/1931	3	P.W. Fattig	32.8492	-83.644		INHS	
GA	Bibb	Macon, Ocmulgee River	7/29/1931	1	P.W. Fattig	32.8574	-83.6365		INHS	
GA	Bibb		August	A		32.807447	-83.686847	*County only record		Berner 1977
GA	Bryan-Evans	Canoochee R, 5 mi east of Claxton and 1/2 mi downstream	8/6/1958			32.148251	-81.781345			Scott et al. 1959

		from the bridge on U.S. Hwy 280 at the Bryan-Evans county line								
GA	Burke	Hancock Landing	June/July 1952			33.164886	-81.764744			Scott et al. 1959
GA	Decatur	Spring Creek	7/23/1946	8	P.W. Fattig	30.855	-84.584		INHS	
GA	Decatur	Spring Creek	8/20/1946	8	P.W. Fattig	30.855	-84.584		INHS	
GA	Decatur	Spring Creek	8/5/1947	1	P.W. Fattig	30.855	-84.584		INHS	
GA	Decatur		July-August	A		30.887059	-84.595105	*County only record		Berner 1977
GA	Dougherty	Albany	7/30/1931	1	P.W. Fattig	31.5791	-84.1557		INHS	
GA	Dougherty			A		31.598098	-84.124613	*County only record		Berner 1977
GA	Effingham	Ebenezer Landing, 52 mi from mouth of Savannah R	7/30/1952			32.378847	-81.182193			Scott et al. 1959
GA	Effingham		July	L, A		32.325616	-81.31951	*County only record		Berner 1977
GA	Richmond			A		33.489903	-82.043137	*County only record		Berner 1977

GA	Tattnall	Choopee R, 3 mi west of Reidsville and 1/4 mi upstream from the bridge on U.S. Hwy 380	8/7/1958			32.107879	-82.175253			Scott et al. 1959
GA		Savannah R				32.079391	-81.074968			McCafferty 1975
GA										Berner and Pescador 1988
IL			08/11/1896	1	C.A. Hart	40	-89.25		INHS	
IL	Champaign	Champaign, Boneyard Creek	09/21/1892	1	C.A. Hart	40.112	-88.237		INHS	
IL	Champaign	Urbana, Boneyard Creek	9/20/1909	1		40.11056	-88.20722		INHS	
IL	Champaign	Urbana, Boneyard Creek	8/23/1943	1	H.B. Petty	40.11056	-88.20722		INHS	
IL	Gallatin	Shawnee-town	10/3/1942	1	T.H. Frison, H.H. Ross	37.69392	-88.13488		INHS	
IL	Hardin	Elizabethtown, Ohio River	7/14/1948	1	H.H. Ross, H.B. Mills	37.44514	-88.30372		INHS	

IL	Henderson	Oquawka, MS River	9/26/1947	9 F	H.H. Ross	40.93725	-90.95701		INHS	
IL	Henderson	Oquawka, MS River	9/26/1947	8 F	H.H. Ross	40.93725	-90.95701		INHS	
IL	Henderson	Oquawka, MS River	9/26/1947	12 F	H.H. Ross	40.93725	-90.95701		INHS	
IL	Jackson	Grand Tower, MS River	08/14/1898		C.A. Hart	37.62639	-89.49778		INHS	
IL	Jackson	Grand Tower, MS River	08/14/1898	1	C.A. Hart	37.62639	-89.49778		INHS	
IL	Jackson	Grand Tower, MS River	08/14/1898	1 M	C.A. Hart	37.62639	-89.49778		INHS	
IL	Madison	Alton, Illinois River	8/29/1913	1		38.88833	-90.18582		INHS	
IL	Mason	White Oak Run	08/14/1896	1	C.A. Hart	40.25673	-90.08669		INHS	
IL	McLean	Bloomington	07/01/1892 - 7/31/1892	1	C.C. Adams	40.49156	-89.01345		INHS	
KS	Dickinson	Abilene		13		38.9174	-97.2141		INHS	
KS	Dickinson	Abilene			H.H. Ross	38.9174	-97.2141		INHS	
KS	Ellsworth	Ellsworth		2		38.7303	-98.228		INHS	
KY		Reelfoot L., Reelfoot Lake	8/9/1940	2	G.E. Quimby	36.506847	-89.334802	*Estimated GPS/could be TN	INHS	

LA	Caddo	Red River near Lachute	8/11/1986	3 F	B Shipley	32.252851	-93.498956		CSUC	
LA	Natchitoches	Natchitoches	7/2/1956		J.E. Sublette	31.77546	-93.0816			Scott et al. 1959
LA	Red River	Red River near Grand Bayou, T.13N, R.11W, S.2	8/22/1979		TM Lager	32.103487	-93.44911			Lager. 1985
LA										Berner and Pescador 1988
LA								Very immature larvae, tentative ID		McCafferty 1975
Manitoba		Wellwood	8/14/1947	1		50.040586	-99.333651	*approx. GPS	INHS	
MO	New Madrid	Mississippi River, Island 8 Secondary Channel	July-August 1984	8 L		36.621909	-89.311309			Aartilla 1988
MO	Wayne	Williamsville	6/25/1948	2	E.C. Becker, et al.	36.97111	-91.54944		INHS	

MS	Bolivar	Mississippi River, Hurricane Point/Chevrons at Dennis Landing	10/22/2015	3 L	ABH, WTS, BRL, JAC, CAO	34.01816	-90.94228	*This study – may be *T. primus*		
MS	Bolivar	Mississippi River, Knowlton Secondary Channel	11/4/2014	1 L	ABH, WTS, BRL, JAC	34.03062	-90.91422	*This study – may be *T. primus*		
MS	Coahoma	Mississippi River, Island 63 Secondary Channel	6/11/2014	20 L	ABH, WTS, BRL, JAC	34.2683	-90.73325	*This study – may be *T. primus*		
MS	Forrest		August	A		31.303114	-89.248672	*County only record		Berner 1977
MS	Issaquena	Mayersville Natural Bank	Jun-78	187 L		32.880046	-91.074285			Mathis et al. 1981
MS	Issaquena	Mississippi River, Levee Rd, at lights	8/1/1983	2 F	F Jones	32.916099	-91.060773		CSUC	
MS	Itawamba	Bull Mountain Creek at Hwy 25	7/25-26/1954		C.D. Hynes	34.100857	-88.424259			Scott et a. 1959
MS	Itawamba		August	A		34.309053	-88.384618	*County only record		Berner 1977

MS	Lawrence	Pearly River at Hwy 84	8/16-17/1954		C.D. Hynes	31.566235	-90.101005			Scott et a. 1959
MS	Monroe		July	A		33.915728	-88.512752	*County only record		Berner 1977
MS	Munroe	Tombigbee River	7/24/1954		C.D. Hynes	33.696496	-88.483653			Scott et a. 1959
MS	Pike	Bayou Chitto at Hwy 24	8/18-19/1954		C.D. Hynes	31.117897	-90.262025			Scott et a. 1959
MS	Pike		August	A		31.293111	-90.432013	*County only record		Berner 1977
MS	Smith	Leaf River	8/15/1954		C.D. Hynes	31.950639	-89.406293			Scott et a. 1959
MS	Smith		August	A		32.051958	-89.486591	*County only record		Berner 1977
MS	Washington	Leota Dike Field	6/25-29/1979			33.088388	-91.163802			Beckett et al. 1983
MS	Washington	Leota Dike Field	6/25-29/1979	122 L		33.111814	-91.131952			Mathis et al. 1981
MS	Washington	Mississippi River, Kentucky Bend	Jun-78	7 L		33.173338	-91.083703			Mathis et al. 1981
MS	Washington	Mississippi River, Lakeport Towhead Natural Bank/American Cuttoff	Jun-78	39 L		33.268915	-91.115368			Mathis et al. 1981

MS	Yalobusha	Otoucalofa Creek-Water Valley		18		34.160058	-89.528372			Knight and Cooper 1989
MS										Berner and Pescador 1988
NC	Bladen	South River				34.762004	-78.408744			Lenat and Penrose 1987
NC	Franklin	Tar River				36.09508	-78.298371			Lenat and Penrose 1987
NE	Otoe	Nebraska City	8/22/1947	1	H.H. Ross	40.67667	-95.85889		INHS	
OK	Comanche	Fort Sill				34.586039	-98.420281			Zuillig et al. 2006
SC	Aiken	Beulah Pond	7/22/1952, 7/29/1952, 8/8/1952		William Cross	33.439022	-81.536704			Scott et a. 1959
SC	Aiken	Near mouth of Upper Three Runs	June/July 1952			33.353978	-81.687264			Scott et a. 1959
SC	Aiken	Savannah R-5 mi below Peyre, Steel Cr	7/8/1951		Dolan	33.524485	-82.007386			Scott et a. 1959
SC	Aiken		July, August	A		33.504247	-81.798785	*County only record		Berner 1977

SC	Allendale	Savannah River, Site 5	June 1951, September 1955			33.084613	-81.603859			Patrick et al. 1966
SC	Allendale	Savannah River, Site 6	June 1951, September 1955			33.023744	-81.510983			Patrick et al. 1966
SC	Allendale		July, August	L		32.982369	-81.3319	*County only record		Berner 1977
SC	Barnwell	Near mouth of Steel Creek, 72-155 miles from the mouth of the river.				33.125235	-81.626077			Scott et a. 1959
SC	Florence	Pee Dee R, ca 800 m upstream of Hwy 76/301 bridge nr Florence	1999		Smith	34.205925	-79.547775			McCafferty and Meyer 2008
SC	Hampton	Savannah River				32.565035	-81.331413			Scott et a. 1959
SC	Marion	Pee Dee R, ca 800 m upstream of Hwy 76/301 bridge, nr Florence	1999		Smith	34.167854	-79.414843			McCafferty and Meyer 2008

SC										Berner and Pescador 1988
TN	Lake	Reelfoot Lake	8/9/1940	1	G.E. Quimby	36.36269	-89.43183		INHS	
TN	Lake	Reelfoot Lake	8/9/1940	4	G.E. Quimby	36.36269	-89.43183		INHS	
TN	Lake	Reelfoot Lake	8/9/1940	1 M, 1 F	G.E. Quimby	36.36269	-89.43183		INHS	
TN		No locality								Burks 1953
TX	Brazos	Brazos River; Hidalgo Falls, SW Millican, dirt road off FM 159	7/31/1992	>100 MF	JC Abbott	30.394692	-96.176158			Baumgardner et al. 1997
TX	Milam	Little R. at St. Hwy. 36, ca. 1 mi S Cameron	9/8/1993	26 M 94 F	RJ Garono	30.835797	-96.947595			Baumgardner et al. 1997
WI	Walworth	Geneva Lake, E side near Dunlop's	10/12/1881	1		42.56046	-88.46072		INHS	

Table D.7. Distributional data for *Pentagenia vittigera* (Ephemeroptera: Palingeniidae) from published literature, major collections, and this study. Stage: L = larva, A = adult, M = adult male, F = adult female, I = subimago.

State	County	Location	Date	No./ Stage	Collect-ors	Latitude	Longitude	Comments	Collect-ion	Citation
AR	Chicot	Mississippi River, Island 86	Jun-78	4 L		33.22186	-91.109173			Mathis et al. 1981
AR	Chicot	Mississippi River, Island 88 Natural Bank	Jun-78	28 L		33.15984	-91.094886			Mathis et al. 1981
AR	Chicot	Mississippi River, Seven Oaks Natural Bank	Jun-78	17 L		33.18848	-91.097631			Mathis et al. 1981
AR	Chicot	Mississippi River, Lakeport Towhead Channel	10/10/1984	4 L		33.23094	-91.118757			Aartilla 1988
AR	Fulton	Mammoth Springs	6/6/1937	2 F	H.H. Ross	36.49487	-91.53654		INHS	
AR	Fulton	Mammoth Springs	6/6/1937	2 F	H.H. Ross	36.49487	-91.53654		INHS	
AR	Lee	Mississippi River, Mhoon Landing	02/27/08	3 L	ERDC	34.727320	-90.477070	In sturgeon diet		
AR	Phillips	Island 62 Secondary Channel	6/11/2014	1	ABH, WTS, BRL, JAC	34.28801	-90.75537	*This study		

AR	Phillips	Island 62 Secondary Channel	6/11/2014	1	ABH, WTS, BRL, JAC	34.29314	-90.75492	*This study		
AR	Phillips	Island 64 Lower	8/20/2015	1		34.19976	-90.86861797	*This study		
AR	Phillips	Island 64 Lower	8/20/2015	2		34.19899	-90.86828504	*This study		
AR	Phillips	Island 64 Upper	8/20/2015	5		34.21951	-90.85947398	*This study		
AR	Phillips	Kangaroo Point Secondary Channel	6/12/2014	1	ABH, WTS, BRL, JAC	34.37307	-90.70468	*This study		
AR	Phillips	Kangaroo Point Secondary Channel	6/23/2015	1	ABH, WTS, BRL, JAC, CAO	34.37035	-90.71871	*This study		
AR	Phillips	Main Channel	6/12/2014	1	ABH, WTS, BRL, JAC	34.37463	-90.6804	*This study		
AR	Washing-ton	Low Hollow and Cove Creeks 15 mi S. Prairie Grove	1966	5 M	Peters and Warren	35.97777	-94.319773			McCafferty and Provonsha 1978
AR	Washing-ton	Low Hollow and Cove Creeks, 15 mi. S. Prairie Grove	9/1/1968	4 M	B Schiefer and J Kimbro ugh	35.7886	-94.369877			McCafferty and Provonsha 1978

AR	Washing-ton	Low Hollow and Cove Creeks, 15 mi. S. Prairie Grove	4/20/1969	1 M	B Schiefer	35.7886	-94.369877			McCafferty and Provonsha 1978
FL	Gulf	Apalachicola River Buoy 40 Mile 11A	7/14/1977	4		29.827236	-85.031383		FDEP	
FL	Holmes	Choctawhatchee River 2 mi SW Curry Ferry Izagora	3/11/1999	1		30.900861	-85.876028		FDEP	
FL	Liberty	Apalachicola River near mile 20.1 at head of Brusy Cr	7/6/1999	4		30.003778	-85.055		FDEP	
FL										Berner and Pescador 1988
GA	Baker	Newton	1/1/1954	1 A	C.O. Mohr	31.3134	-84.3355		INHS	
GA	Baker	Newton	12/31/1954	1 L	C.O. Mohr	31.3134	-84.3355		INHS	
GA	Clark	Athens	7/14/1970	2 M	W.P. McCafferty and T.L. Harris	33.96026	-83.398471			McCafferty 1975
GA										Berner and Pescador 1988
IA	Clay		VII-26-1987			43.09775	-95.077526			McCafferty et

										al. 2003
IA	Clinton	Clinton				41.80622	-90.19044			McCafferty et al. 2003
IA	Decatur	Thompson River				40.72071	-93.87921		IA DNR	
IA	Des Moines	at Burlington under US-34	8/29/1938	1 M	J.S. Ayars	40.81235	-91.09885		INHS	
IA	Des Moines	at Burlington under US-34	6/10/1939	2 M	J.S. Ayars	40.81235	-91.09885		INHS	
IA	Des Moines	at Burlington under US-34	6/11/1939	1 F	J.S. Ayars	40.81235	-91.09885		INHS	
IA	Des Moines	Burlington				40.80785	-91.118538			McCafferty et al. 2003
IA	Dickinson					43.4541	-95.078917			McCafferty et al. 2003
IA	Hancock	East Branch Iowa River				42.94442	-93.57652		IA DNR	
IA	Henry	Mount Pleasant				40.96755	-91.54186			McCafferty et al. 2003
IA	Jackson	Mississippi River at Sabula	VIII-06-1946			42.06944	-90.169988			McCafferty et al. 2003
IA	Jackson	Sabula	8/6/1946	1 F		42.07153	-90.17162		INHS	
IA	Lee	Fort Madison				40.61757	-91.353717			McCafferty et al. 2003
IA	Lee	Keokuk, Mississippi River				40.38441	-91.401898			McCafferty et al. 2003
IA	Lee	Mississippi River				40.60375	-91.369541			McCafferty et al. 2003
IA	Monona	Little Sioux River				41.96507	-95.97294		IA DNR	
IA	Muscatine	Fairport				41.43512	-90.904478			McCafferty et al. 2003

IA	Muscatine	Muscatine				41.40599	-91.057292			McCafferty et al. 2003
IA	Page	East Nishnabotna River				40.78555	-95.38562		IA DNR	
IA	Page	Shenandoa	VII-09-1963			40.76374	-95.380293			McCafferty et al. 2003
IA	Polk		7/3/1939	1 A	B.G. Berger	41.683	-93.584		INHS	
IA	Pottawattamie	Boyer River				41.45821	-95.91531		IA DNR	
IA	Scott	Buffalo				41.45565	-90.728373			McCafferty et al. 2003
IA	Scott	Davenport				41.48723	-90.629631			McCafferty et al. 2003
IA	Story	Ames	VIII-11-1991			42.01867	-93.596363			McCafferty et al. 2003
IA	Story	South Skunk River, Iowa St Univ Hinds Irrigation Farm, Ames	IX-19-1987, VI-12-1991, II-28-1992, VI-15-1992			42.06325	-93.62014			McCafferty et al. 2003
IA	Story	South Skunk River, Soper's Mill Park	VII-11-1992			42.10596	-93.5712			McCafferty et al. 2003
IA	Van Buren	Des Moines River, Farmington	VI-12-1992			40.6367	-91.743572			McCafferty et al. 2003
IA	Van Buren	Keosauqua				40.7336	-91.956141			McCafferty et al. 2003
IA	Van Buren	Lacy Keosauqua	VIII-29-1992			40.7175	-91.979966			McCafferty et al. 2003

		Street Park								
IA	Warren	Middle River				41.42468	-93.58748		IA DNR	
IA	Washing-ton					41.29538	-91.68835			McCafferty et al. 2003
IA	Webster	Des Moines River, Dolliver St Park	V-18-1992			42.39049	-94.078282			McCafferty et al. 2003
IA	Woodbury	Little Sioux River				42.25135	-95.90642		IA DNR	
IA		Mississippi River, Keokuk								Berner and Pescador 1988
IL	Adams	Mississippi River, Quincy	6/6-9/20	A		39.93106	-91.415244			Burks 1953
IL	Adams	Quincy	7/13/1937	1 M	C.O. Mohr, B.D. Burks	39.93363	-91.41811		INHS	
IL	Adams	Quincy	6/7/1939	1 F	B.D. Burks, G.T. Riegel	39.93363	-91.41811		INHS	
IL	Adams	Quincy	6/7/1939	1 M	B.D. Burks, G.T. Riegel	39.93363	-91.41811		INHS	

IL	Adams	Quincy	6/8/1939	1 M	B.D. Burks, G.T. Riegel	39.93363	-91.41811		INHS	
IL	Adams	Quincy	7/6/1939	1 M	C.O. Mohr, G.T. Riegel	39.93363	-91.41811		INHS	
IL	Adams	Quincy	7/6/1939	1 F	C.O. Mohr, G.T. Riegel	39.93363	-91.41811		INHS	
IL	Adams	Quincy	6/14/1940	1 F	T.E. Musselman	39.93363	-91.41811		INHS	
IL	Adams	Quincy	6/25/1940	1 A	C.O. Mohr, G.T. Riegel	39.93363	-91.41811		INHS	
IL	Adams	Quincy	6/25/1940	1 M	C.O. Mohr, G.T. Riegel	39.8692	-91.3086		INHS	
IL	Adams	Quincy	8/1/1940	1 F	T.E. Musselman	39.93363	-91.41811		INHS	
IL	Adams	Quincy	07/30/1898	1 A		39.93363	-91.41811		INHS	
IL	Adams	Quincy	07/30/1898	3 A		39.93363	-91.41811		INHS	
IL	Adams	Quincy	08/02/1898	2 A		39.93363	-91.41811		INHS	
IL	Adams	Quincy	08/03/1898	4 A		39.93363	-91.41811		INHS	
IL	Alexander	Cairo	6/27/1905	1 A		37.0053	-89.1764		INHS	
IL	Alexander	Cairo	6/27/1905	1 F		37.0053	-89.1764		INHS	

IL	Alexander	Cairo	8/1/1905	1 A		37.0053	-89.1764		INHS	
IL	Alexander	Cairo	6/10/1907	1 A		37.0053	-89.1764		INHS	
IL	Alexander	Cairo	6/10/1907	1		37.0053	-89.1764		INHS	
IL	Alexander	Cairo	6/10/1907	1 F		37.0053	-89.1764		INHS	
IL	Alexander	Cairo	7/15/1937	1 F	C.O. Mohr, B.D. Burks	37.0053	-89.1764		INHS	
IL	Alexander	Cairo	6/21/1940	1 F	C.O. Mohr, G.T. Riegel	37.0053	-89.1764		INHS	
IL	Alexander	Cairo	6/21/1940	1 L	C.O. Mohr, G.T. Riegel	37.0053	-89.1764		INHS	
IL	Alexander	Cairo	08/14/1891	1 A	C.A. Hart, S. Shiga	37.0053	-89.1764		INHS	
IL	Alexander	Cairo	6/6-9/20	A		36.99667	-89.179433			Burks 1953
IL	Calhoun	at island [Twelvemile Island], 13 mi upstr. Grafton		1 L		39.05635	-90.58669		INHS	
IL	Calhoun	Hardin	6/8/1932	1 M	H.L. Dozier	39.15665	-90.61468		INHS	
IL	Calhoun	Kampsville	8/23/1913	1 A		39.29897	-90.60725		INHS	
IL	Calhoun	Kampsville	8/23/1913	1 M		39.29897	-90.60725		INHS	
IL	Carroll	Savanna	07/22/1892		C.A. Hart, S.A. Forbes	42.09622	-90.16227		INHS	

IL	Cham-paign	Champaign	9/13/1938	1 F	H.H. Ross, B.D. Burks	40.112	-88.237		INHS	
IL	Cham-paign	Champaign	6/6-9/20	A		40.10647	-88.261662			Burks 1953
IL	Cham-paign	Urbana	7/5/1907	1 A		40.11056	-88.20722		INHS	
IL	Cham-paign	Urbana	9/13/1909	1 A		40.11056	-88.20722		INHS	
IL	Cham-paign	Urbana	9/20/1909	1 A		40.11056	-88.20722		INHS	
IL	Cham-paign	Urbana	6/17/1937	1 F	C.O. Mohr	40.11056	-88.20722		INHS	
IL	Cham-paign	Urbana	9/11/1937	1 F	G.T. Riegel	40.11056	-88.20722		INHS	
IL	Cham-paign	Urbana	06/16/1887	1 A	C.A. Hart	40.11056	-88.20722		INHS	
IL	Cham-paign	Urbana	06/17/1887	1 A	C.A. Hart	40.11056	-88.20722		INHS	
IL	Cham-paign	Urbana	6/6-9/20	A		40.10758	-88.207123			Burks 1953
IL	Clinton	0.6 mi S Carlyle Lake dam.	8/9/1943	1 F	M.W. Sanderson, D. Leighton	38.6098	-89.3575		INHS	
IL	Clinton	Carlyle	6/6-9/20	A		38.61245	-89.368628			Burks 1953
IL	Cook	Chicago	7/8/1937	6 F	T.H. Frison, H.H. Ross	41.8495	-87.6009		INHS	
IL	Cook	Chicago	6/6-9/20	A		41.81599	-87.678428			Burks 1953

IL	Effingham	Effingham (center of)	6/20/1927	1 A	T.H. Frison, R.D. Glasgow	39.12234	-88.58729		INHS	
IL	Ford	Gibson City	8/22/1938	1 F	H.H. Ross	40.4655	-88.3762		INHS	
IL	Ford	Gibson City	6/6-9/20	A		40.4671	-88.374132			Burks 1953
IL	Gallatin	Shawnee-town	6/21/1927	1 A	T.H. Frison, R.D. Glasgow	37.69392	-88.13488		INHS	
IL	Hardin	Elizabeth-town	6/22/1924	1 F	H.H. Ross, H.L. Dozier, O. Park	37.44514	-88.30372		INHS	
IL	Hardin	Elizabeth-town	6/22/1927	1 A	T.H. Frison, R.D. Glasgow	37.44514	-88.30372		INHS	
IL	Hardin	Elizabeth-town	6/25/1932	1 F	H.H. Ross, H.L. Dozier, O. Park	37.44514	-88.30372		INHS	
IL	Hardin	Elizabeth-town	6/6-9/20	A		37.44538	-88.304479			Burks 1953
IL	Hardin	Rosiclare	7/5/1935	1 M	T.H. Frison, C.O. Mohr	37.42361	-88.34611		INHS	

IL	Hardin	Rosiclare	6/6-9/20	A		37.41173	-88.355157			Burks 1953
IL	Henderson	Oquawka	9/26/1947	1 M	H.H. Ross	40.93725	-90.95701		INHS	
IL	Henderson	Oquawka	6/6-9/20	A		40.93751	-90.955881			Burks 1953
IL	Jackson	Carbondale	6/13/1944	1 F	T.H. Frison, M.W. Sanderson	37.72722	-89.21667		INHS	
IL	Jackson	Carbondale	6/6-9/20	A		37.7254	-89.233953			Burks 1953
IL	Jackson	Grand Tower	7/12/1909	1 A		37.62834	-89.50663		INHS	
IL	Jackson	Murphys-boro	6/20/1939	1 F	B.D. Burks, G.T. Riegel	37.7684	-89.3401		INHS	
IL	Jackson	Murphys-boro	6/6-9/20	A		37.75978	-89.33287			Burks 1953
IL	Jersey	Grafton, Evans Street Landing	7/5/1938	1 M	B.D. Burks, Boesel	38.96785	-90.43183		INHS	
IL	Jersey	Grafton, Evans Street Landing	7/5/1938	F M	B.D. Burks, Boesel	38.96785	-90.43183		INHS	
IL	Jersey	Grafton, Evans Street Landing	7/6/1938	1 M	B.D. Burks, Boesel	38.96785	-90.43183		INHS	
IL	Jersey	Grafton, Evans Street Landing	9/19/2000	1 F 1 M	J.D. Tucker	38.96785	-90.43183		INHS	
IL	Jersey	Grafton, Evans Street Landing		1 L		38.96785	-90.43183		INHS	

IL	Jersey	Illinois River, Grafton	6/6-9/20	A		38.96793	-90.417662			Burks 1953
IL	Jersey	Pere Marquette State Park	6/6-9/20	A		38.98266	-90.514926			Burks 1953
IL	Jersey		7/6/1938	1 M	B.D. Burks, Boesel	38.9764	-90.5429		INHS	
IL	Jo Daviess	East Dubuque	7/21/1927	1 A	T.H. Frison, R.D. Glasgow	42.49213	-90.65106		INHS	
IL	La Salle	1.5 km S Utica	8/21/1997		R.E. DeWalt	41.327	-89.0056		INHS	
IL	Lake	Waukegan	6/10/1938	1 F	C.O. Mohr, B.D. Burks	42.35737	-87.82995		INHS	
IL	Lake	Waukegan	6/6-9/20	A		42.35704	-87.851012			Burks 1953
IL	Lee	Dixon	6/25/1947	1 A	B.D. Burks	41.84557	-89.48453		INHS	
IL	Lee	Dixon	6/6-9/20	A		41.83819	-89.489773			Burks 1953
IL	Marion	Centralia	6/17/1947	1 A	L.J. Stannard	38.525	-89.1329		INHS	

IL	Marion, Washing-ton, Clinton, Jefferson	Centralia	6/6-9/20	A		38.52511	-89.131465			Burks 1953
IL	Mason	at mouth, at Forbes Biological Station, INHS Field Station	6/9/1940		J. S. Ayars, Hawkins	40.347	-89.996		INHS	
IL	Mason	Havana	07/01/1897	1 M	C.A. Hart, E.V. Bronson	40.29444	-90.06885		INHS	
IL	Mason	Havana	6/6-9/20	A		40.29047	-90.058114			Burks 1953
IL	Mason	Havana, Quiver Chute (narrowing of channel below Quiver Lake)	07/13/1895		C.A. Hart	40.33453	-90.04713		INHS	
IL	McLean	Blooming-ton	07/19/1892	1 F	C.C. Adams	40.49156	-89.01345		INHS	
IL	McLean	Blooming-ton	6/6-9/20	A		40.47989	-88.990336			Burks 1953
IL	Mercer	Keithsburg	6/8/1932	1 M	H.H. Ross, C.O. Mohr	41.09798	-90.94775		INHS	
IL	Mercer	Keithsburg	6/14/1932	1 A	T.H. Frison, C.O.	41.09798	-90.94775		INHS	

					Mohr					
IL	Mercer	Keithsburg	6/6-9/20	A		41.101559	-90.947981			Burks 1953
IL	Morgan	Illinois River, Meredosia	6/6-9/20	A		39.83196	-90.565042			Burks 1953
IL	Morgan	Jacksonville	08/17/1898	1 A		39.73389	-90.22889		INHS	
IL	Peoria	Chillicothe adj. to IL-29	6/24/2004	1 F	J.E. Petzing	40.9185	-89.4872		INHS	
IL	Peoria	Illinois River, Peoria	6/6-9/20	A		40.66916	-89.613463			Burks 1953
IL	Peoria	Peoria	6/12/1938	1 F	F.F. Hasbrouck	40.69361	-89.58889		INHS	
IL	Peoria	Peoria	6/15/1938	1 M	F.F. Hasbrouck	40.69361	-89.58889		INHS	
IL	Peoria	Peoria	6/30/1938	1 A	F.F. Hasbrouck	40.69361	-89.58889		INHS	
IL	Peoria	Peoria	8/3/1938	1 A	F.F. Hasbrouck	40.69361	-89.58889		INHS	
IL	Pike	Florence, public boat ramp S IL-106; 18km NE Pittsfield	8/20/1913	1 A		39.63079	-90.60899		INHS	

IL	Pike	Jackson Island opposite Hannibal, Missouri	9/6/1940	1 F	G.T. Riegel	39.718	-91.3513		INHS	
IL	Pike	Meredosia, West Shore		1 L		39.831	-90.5673		INHS	
IL	Pike	Meredosia, West Shore		7 L		39.831	-90.5673		INHS	
IL	Pike	Pike	6/25/1906	1 A		39.458	-91.045		INHS	
IL	Pope	Golconda	9/20/1947	1 M	P.W. Smith	37.3672	-88.4864		INHS	
IL	Pope	Golconda	9/20/1947	1 F	P.W. Smith	37.3672	-88.4864		INHS	
IL	Pope	Golconda	6/6-9/20	A		37.36294	-88.48689			Burks 1953
IL	Randolph	Pierre Mendard's Home	6/14/1969	1 M	W.U. Brigham	37.9703	-89.892679	*County only record	INHS	
IL	Rock Island	Carbon Cliff	6/6-9/20	A		41.49355	-90.395118			Burks 1953
IL	Rock Island	Rock Island	6/7/1939	1 F	B.D. Burks, G.T. Riegel	41.51346	-90.58287		INHS	
IL	Rock Island	Rock Island	6/6-9/20	A		41.50009	-90.59591			Burks 1953
IL	Saline	Harrisburg	6/15/1934	1 F	D.M. DeLong, H.H. Ross	37.74535	-88.54635		INHS	
IL	Saline	Harrisburg	6/6-9/20	A		37.73569	-88.545631			Burks 1953

IL	St. Clair	nr. New Athens	6/6/1942	1 M	H.H. Hoogstraal	38.3273	-89.8812		INHS	
IL	Stephen-son	0.5 km WSW McConnell	6/23/1926	1 A	D.H. Thompson	42.43214	-89.73713		INHS	
IL	Stephen-son	2 mi E Winslow, Brewster Public Boat Ramp	8/1/1998	1 F	R.E. DeWalt	42.495	-89.768		INHS	
IL	Stephen-son	6 km E Freeport	6/10/1948	1 A	B.D. Burks, L.J. Stannard, P.W. Smith	42.3026	-89.5595		INHS	
IL	Stephen-son	Freeport	6/6-9/20	A		42.29407	-89.63834			Burks 1953
IL	Stephen-son	Rock River, McConnell	6/6-9/20	A		42.43454	-89.731461			Burks 1953
IL	Union	Anna	6/20/1939	1 F	B.D. Burks, G.T. Riegel	37.46028	-89.24694		INHS	
IL	Union	Anna	6/6-9/20	A		37.460737	-89.242718			Burks 1953
IL	Wabash	Mount Caramel	6/6-9/20	A		38.40744	-87.753854			Burks 1953
IL	Wabash	Mt. Carmel	7/28/1938	1 M	B.D. Burks, Boesel	38.404	-87.7516		INHS	

IL	Wabash	Mt. Carmel	7/28/1938	1 F	B.D. Burks, Boesel	38.404	-87.7516		INHS	
IL	Wabash	Mt. Carmel	6/25/1947	1 A	B.D. Burks	38.404	-87.7516		INHS	
IL	Whiteside	Fulton	7/28/1946	1 M		41.86467	-90.17003		INHS	
IL	Whiteside	Fulton	7/28/1946	1 F		41.86467	-90.17003		INHS	
IL	Whiteside	Fulton	7/28/1946	2 F		41.86467	-90.17003		INHS	
IL	Whiteside	Fulton	7/30/1946	1 F		41.86467	-90.17003		INHS	
IL	Whiteside	Fulton	7/30/1946	1 M		41.86467	-90.17003		INHS	
IL	Will	Braidwood (Custer Park), Site 6 R or L	8/14/1979	1 A		41.2604	-88.1395		INHS	
IL	Winne-bago	Pecatonica River State Hwy 70	8/16/1991	2 L	M.A. Harris	42.3695	-89.2622		INHS	
IL	Winne-bago	Rock River, Rockton	6/6-9/20	A		42.44997	-89.070102			Burks 1953
IL	Winne-bago	Rockton	7/2/1931	1 M	T.H. Frison, H.H. Ross, C. Betten	42.4525	-89.07222		INHS	
IL	Winne-bago	Winnebago County Camp-ground	6/22/2010	1 F	R.E. DeWalt, M.M. Brown, E.W. Hernandez	42.45994	-89.23985		INHS	

IL		Rock River, Carbon Cliff	8/13/1925	3 L	D.H. Thompson				INHS	
IL		Shepherd, Levee Township	6/6-9/20	A		39.72442	-91.351724			Burks 1953
IN	Fountain	Wabash River		L		40.12271	-87.406009			
IN	Madison	Anderson	8/10/1938	1 F	H.H. Ross, B.D. Burks	40.11635	-85.67974		INHS	
IN	Martin	0.5 km SSW Shoals	6/21/2006	2 M	R.E. DeWalt	38.6591	-86.8023		INHS	
IN	Pike	Petersburg	6/3/1936	1 M	C.O. Mohr, B.D. Burks	38.5124	-87.2892		INHS	
IN		Wabash R								Berner and Pescador 1988
IN										Berner and Pescador 1988
KS	Barton	Arkansas R, 1 mi S. Dundee	7/14/1976	A	D.G. Huggins & P.M. Liechti	38.29299	-98.892877			Liechti 1981
KS	Barton	Arkansas R, 1 mi S. Dundee			D.G. Huggins & P.M. Liechti	38.29299	-98.892877			Liechti 1981

KS	Barton	Arkansas River, 1 mi S Dundee (sec 21 T20S, R14W), UV light	7/14/1976	1 A	DG Huggins and PM Liechti	38.294	-98.888917			Liechti 1981
KS	Douglas	Kansas River at Lecompton bridge (sec 34, T11S, R18E)	10/9/1975	1 L	DG Huggins	39.04876	-95.387541			Liechti 1981
KS	Douglas	Kansas River, Lecompton Bridge			D.G. Huggins	39.04741	-95.393024			Liechti 1981
KS	Douglas	Lecompton Bridge	10/9/1975	L	D.G. Huggins	39.04741	-95.393024			Liechti 1981
KS	Jefferson	Kansas River at Lecompton bridge (sec 34, T11S, R18E)	9/11/1975	1 L	DG Huggins	39.04876	-95.387541			Liechti 1981
KS	Jefferson	Kansas River, Lecompton Bridge			D.G. Huggins & J. Wagner	39.05048	-95.387569			Liechti 1981
KS	Jefferson	Lecompton Bridge	9/11/1975	L	D.G. Huggins & J. Wagner	39.05048	-95.387569			Liechti 1981

KS	Johnson	Kansas R, 2 mi W & 2.2 mi N Sunflower	8/29/1975	L	D.G. Huggins	38.97586	-95.031459			Liechti 1981
KS	Johnson	Kansas R, 2 mi W & 2.2 mi N Sunflower			D.G. Huggins	38.97586	-95.031459			Liechti 1981
KS	Johnson	Kansas River, 2 mi W and 2.2 mi N Sunflower (sec 23, T12S, R21E)	8/29/1975	1 L	DG Huggins	39.06091	-94.862322			Liechti 1981
KS	Johnson	Kansas River, 2 mi W and 2.2 mi N Sunflower (sec 23, T12S, R21E)	9/9/1975	1 L	DG Huggins	39.06091	-94.862322			Liechti 1981
KS	Leaven-worth	Kansas R, 3.6 mi W & 0.6 mi S Fall Leaf	9/9/1975	L	D.G. Huggins	38.97153	-95.115593			Liechti 1981
KS	Leaven-worth	Kansas R, 3.6 mi W & 0.6 mi S Fall Leaf			D.G. Huggins	38.97153	-95.115593			Liechti 1981
KS	Leaven-worth	Kansas River, 2.6 mi W & 0.6 mi S Fall Leaf (sec 34,	9/9/1975	1 L	DG Huggins	38.97389	-95.147649			Liechti 1981

		T12S, R20E)								
KS	Lyon	Cottonwood R 9 mi W Emporia	6/19/1978	L	M.B. DuBois & A. Slater	38.38812	-96.183397			Liechti 1981
KS	Lyon	Cottonwood R 9 mi W Emporia			M.B. DuBois & A. Slater	38.38812	-96.183397			Liechti 1981
KS	Lyon	Cottonwood River 9 mi W Emporia (sec 18, T19S, R10E)	6/19/1978	1 L	MB DuBois and A Slater	38.39885	-96.35518			Liechti 1981
KS	Marshall	Big Blue River 0.5 mi NE Blue Rapids upstream from K-9 hwy bridge	12/19/1979	L	D.G. Huggins	39.68297	-96.633739			Liechti 1981
KS	Marshall	Big Blue River 0.5 mi NE Blue Rapids upstream from K-9 hwy bridge			D.G. Huggins	39.68297	-96.633739			Liechti 1981

KS	Marshall	Big Blue River 0.5 mi NE Blue Rapids upstream from K-9 hwy bridge (Sec 20, T4S, R7E)	12/19/1979	1 L	DG Huggins	39.68777	-96.638849			Liechti 1981
KS	Ottawa	Solomon R 0.6 W Niles	10/7/1980	L	P.M Liechti & L.C. Ferrington	38.96408	-97.4752			Liechti 1981
KS	Ottawa	Solomon River 0.6 W Niles (sec 31, T12S, R1W)	10/7/1980	1 L	PM Liechti and LC Ferrington	38.96922	-97.476443			Liechti 1981
KS	Shawnee	Kansas R 0.5 mi N& 1.3 mi W Valencia	10/13/1975	L	D.G. Huggins	39.07116	-95.753778			Liechti 1981
KS	Shawnee	Kansas R 0.5 mi N& 1.3 mi W Valencia			D.G. Huggins	39.07116	-95.753778			Liechti 1981
KS	Shawnee	Kansas River, 0.5 mi N & 1.3 mi W Valencia (sec 19, T11S, R14E)	10/13/1975	1 L	DG Huggins	39.08457	-95.05097			Liechti 1981

LA	East Baton Rouge	Baton Rouge	9/3/1964	12 M 6 F		30.44767	-91.186136			McCafferty 1975
LA	East Baton Rouge	Mississippi River, Springfield Bend	09/20/01	1 L	ERDC	30.553867	-91.242350	In sturgeon diet		
LA	Red River	Red River near Grand Bayou, T.13N, R.11W, S.2	8/22/1979		TM Lager	32.10349	-93.44911			Lager 1985
LA	St. Charles	MS River near Bonnet Carre	04/21/08	1 L	ERDC	30.023770	-90.477810	In sturgeon diet		
LA										Berner and Pescador 1988
Mani-toba	Winnipeg	Assiniboine River near junction with Red River	1955	A		49.8858	-97.130727			Fremling 1973
Mani-toba			1925		McDun n-ough	50.48981	-99.459984			McCafferty and Randolph 1998
Mani-toba										Berner and Pescador 1988
MI	Grand Traverse	Grand Traverse Bay	10/26/1881	1 A		44.7495	-85.5495		INHS	
MN	Blue Earth	Rapidan	8/18/1938	1 F	J.H. Mohr	44.09267	-94.10821		INHS	
MN	Goodhue	Red Wing	1941			44.60903	-92.602912			Fremling 1973

MN	Goodhue and Wabasha	Lake City	1941			44.45309	-92.267658			Fremling 1973
MN	Hennepin	Minneapolis	1941			44.99585	-93.274641			Fremling 1973
MO	Boone	Missouri River	4/15/1995	L	GWW	38.67214	-92.32192	*County only record		Sarver and Kondratieff 1997
MO	Butler	Poplar Bluff	6/20/1943	1 F	T.H. Frison	36.75694	-90.39278		INHS	
MO	Butler	Poplar Bluff	6/6-9/20	A		36.78131	-90.398534			Burks 1953
MO	Cole	Missouri River, Jefferson City	8/5/1995	A	RJ Sarver	38.5843	-92.173943			Sarver and Kondratieff 1997
MO	Marion	Palmyra	6/8/1939	3 A	G.T. Riegel	39.79417	-91.52306		INHS	
MO	Marion	Palmyra	6/8/1939	2 A	G.T. Riegel	39.79417	-91.52306		INHS	
MO	Marion	Palmyra	6/8/1939	6 F	G.T. Riegel	39.79417	-91.52306		INHS	
MS	Bolivar	Hurricane Point/Chevrons at Dennis Landing	10/22/2015	1 L	ABH, WTS, BRL, JAC, CAO	34.01717	-90.94269	*This study		
MS	Bolivar	Knowlton Secondary Channel	11/4/2014	2 L	ABH, WTS, BRL, JAC	34.03062	-90.91422	*This study		

MS	Coahoma	Friars Point Spring 2014/2015	6/24/2015	2 L	ABH, WTS, BRL, JAC	34.3737	-90.64747	*This study		
MS	Coahoma	Island 63 Lower	8/19/2015	12 L		34.26721	-90.75509699	*This study		
MS	Coahoma	Island 63 Secondary Channel	11/5/2014	1 L	ABH, WTS, BRL, JAC	34.2876	-90.72105	*This study		
MS	Coahoma	Island 63 Secondary Channel	11/5/2014	1 L	ABH, WTS, BRL, JAC	34.28787	-90.72045	*This study		
MS	Coahoma	Island 63 Secondary Channel	10/20/2015	2 L	ABH, WTS, BRL, JAC, CAO	34.26408	-90.74312	*This study		
MS	Coahoma	Island 63 Secondary Channel	10/20/2015	1 L	ABH, WTS, BRL, JAC, CAO	34.26408	-90.74323	*This study		
MS	Coahoma	Island 63 Upper	8/19/2015	15 L		34.31672	-90.73232202	*This study		
MS	Coahoma	Island 63 Upper	8/19/2015	2 L		34.31733	-90.73171701	*This study		
MS	Coahoma	Island 63 Upper	8/19/2015	7 L		34.31764	-90.73137101	*This study		
MS	Coahoma	Main Channel	11/4/2014	2 L	ABH, WTS, BRL,	34.15497	-90.91963	*This study		

					JAC					
MS	Coahoma	Sunflower Dikes Secondary Channel	10/20/2015	15 L	ABH, WTS, BRL, JAC, CAO	34.17962	-90.879	*This study		
MS	Issaquena	Mississippi River, Mayersville Natural Bank	Jun-78	42 L		32.88005	-91.074285			Mathis et al. 1981
MS	Lawrence	Pearl River	8/17/1954	1 M 2 F	C.D. Hynes	31.62719	-90.112085			McCafferty 1975
MS	Washing-ton	Kentucky Bend	Jun-78	9 L		33.17334	-91.083703			Mathis et al. 1981
MS	Washing-ton	Mississippi River, Lakeport Towhead Natural Bank/American Cuttoff	Jun-78	5 L		33.26892	-91.115368			Mathis et al. 1981
MS	Washing-ton	Mississippi River, Leota Dike Field	6/25-29/1979	1 L		33.11181	-91.131952			Mathis et al. 1981
MS										Berner and Pescador 1988
NE	Knox	Lewis and Clark L [Missouri R]	1967		Swanson	42.84323	-97.641621			McCafferty et al. 2001
NE	Lancaster	Lincoln		1 A		40.8	-96.67		INHS	

NE	Madison	Norfolk	1952		Hamilton	42.03882	-97.41994			McCafferty et al. 2001
NE	Nemaha	Missouri River, Peru	7/21/1997		THK	40.4768	-95.700574			McCafferty et al. 2001
NE	Platte	Columbus	1959		Hamilton	41.41751	-97.351982			McCafferty et al. 2001
On-tario		Thunder Bay	1996		Griffiths	48.36809	-89.278436			McCafferty and Randolph 1998
SD	Bon Homme	Missouri River	1967		Swanson	42.87243	-97.759264			Guenther and McCafferty 2008
SD	Yankton	Missouri River				42.8658	-97.39276			Guenther and McCafferty 2008
TN	Knox	Knoxville	05/18/1889	1 A		35.96056	-83.92083		INHS	
TN	Knox	Knoxville	06/22/1891	1 A		35.96056	-83.92083		INHS	
TN	Marion			1A		35.00756	-85.556531	*County only record		Long and Kondratieff 1996
TN	Shelby			1A		35.19411	-90.056173	*County only record		Long and Kondratieff 1996
TN		Chatta-hoochee R								Berner and Pescador 1988
TN		Tennessee R								Berner and Pescador 1988

TN										Berner and Pescador 1988
TX	Live Oak	Nueces River @ Hwy 59; George West, 1 mi E.	5/17/1993	1 M	JC Abbott & WM Godwin	28.33214	-98.086183			Baumgardner et al. 1997
WI	Richland	Orion	8/31/1985	1 L		43.20205	-90.427758			Lillie and Hilsenhoff 1992
WI	Walworth	Geneva Lake, E side near Dunlop's	10/12/1881	1 A		42.56046	-88.46072		INHS	
WI	Walworth	Lake Geneva	10/12/1881	1 A		42.59167	-88.43333		INHS	

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Entomology, GPA: 4.0
B.S., Mississippi College, 2009
General Biology Major, Studio Arts Minor, GPA: 3.84

Experience:
Research Biologist, Contractor - U.S. Army Engineer Research and Development Center, Vicksburg, MS (September 2009 – Present)
Curatorial Assistant, Herbarium of the University of Mississippi (MISS), Oxford, MS (January 2014-December 2014)
Teaching Assistant, Department of Biology, University of Mississippi, Oxford, MS (Genetics, Insect Morphology)
Curatorial Assistant, Clemson University Arthropod Collection (CUAC), Clemson, SC (August 2010—April 2012)
Laboratory Assistant, Mississippi College Dept. of Biological Sciences, Clinton, MS (August 2007-December 2008)

Research Skills:
Macroinvertebrate Taxonomy
Aquatic Macroinvertebrate Field Collection
Museum Curation and Specimen Handling
Database Management
Scanning Electron Microscopy
Scientific Illustrations
PRIMER
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Publications:

Harrison, A.B., W.T. Slack, B.R. Lewis, and J.A. Collins. 2018. A reliable and effective gear type for sampling macroinvertebrates in large rivers. *River Systems*. In press.

Harrison, A.B. and R.E. DeWalt. 2017. Distribution of *Hydroperla fugitans* (Plecoptera: Perlodidae) with notes on diet. *Illiesia* 13(11): 104-110.

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Harrison, A.B., W.T. Slack, A.J. Oliver, C.E. Murphy, L.H. Leonard, C.A. Ochs, and K.J. Killgore. 2018. Benthic macroinvertebrate communities along a gradient of hydrological connectivity within the Lower Mississippi River and its floodplain. American Fisheries Society Mississippi Chapter, Oxford, MS.

Harrison, A.B., C.A. Ochs, W.T. Slack, and K.J. Killgore. 2017. Effects of connectivity on benthic macroinvertebrate community structure of secondary channels in the Mississippi River, USA. International Society for River Science 5th Biennial Symposium. Hamilton, New Zealand.

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Harrison, A.B., W.T. Slack, C.A. Ochs, C.E. Murphy, and K.J. Killgore. 2017. Secondary channel restoration in the Lower Mississippi River. American Fisheries Society Mississippi and Alabama Chapters Meeting. Biloxi, MS.

Nations, T. A.B. Harrison, and J. Goddard. 2016. Black fly species occurring in Mississippi. International Congress of Entomology. Orlando, Florida.

Stark, B.P. and A.B. Harrison. 2016. *Moselia infuscata* (Claassen, 1923) (Plecoptera: Leuctridae), a species complex? North American Plecoptera Symposium. Mount Timpanogos, Utah.

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Harrison, A.B., C.A. Ochs, W.T. Slack, and K.J. Killgore. 2015. Big river benthos: Linking year-round biological response to secondary channel connectivity within the Lower Mississippi River. ERDC Environmental Laboratory Collaborative Conference. Vicksburg, MS.

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Harrison, A.B. 2013. Invertebrates and fishes of the Mississippi River. Guest lecture *for* The Lower Mississippi River: Cultural and Ecological Perspectives, Barksdale Honors College, University of Mississippi, Oxford, MS.

Harrison, A.B. 2013. Like a sturgeon—Feeding habitats of young-of-year river sturgeon (*Scaphirhynchus* spp.) in the Lower Mississippi River. University of Mississippi Biology Seminar Series, Oxford, MS.

Harrison, A.B. and B.P. Stark. 2013. Western North American Leuctridae: A scanning electron microscopy study. 10th North American Plecoptera Symposium, Lamar, PA.

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Harrison, A., W.T. Slack, and K.J. Killgore. 2012. The diets of larval and juvenile pallid and shovelnose sturgeon (*Scaphirhynchus* spp.) in the Lower Mississippi River. Southern Division of the American Fisheries Society. Biloxi, MS.

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Invited Presentations:

Harrison, A.B., C.A. Ochs, W.T. Slack, K.J. Killgore, and C.E. Murphy. 2016. Macroinvertebrate response to a gradient of hydrologic connectivity within the Mississippi River and its floodplain. Lower Mississippi River Conservation Committee Annual Meeting. Memphis, TN.

Harrison, A.B. 2016. Milkweed on the right-of-way initiative: protecting a valuable habitat. Mississippi Native Plant Society Annual Meeting. Picayune, MS.

Peer Review:

River Research and Applications
Environmental Biology of Fishes

Illustrations:

Schnabel, G., A. Amiri, and P. M. Brannen. Field kit- and internet supported fungicide resistance monitoring. In: Thind, T. (Ed.), Fungicide Resistance: Threat and Management. CABI. Book Chapter.

Funded Research:

Macroinvertebrate community response to connectivity of the Mississippi River – U.S. Army Corps of Engineers Mississippi Valley Division MRG&P (2014-present).

Lower Mississippi River secondary channels: macroinvertebrate community response to variable flow regimes and habitat alteration – U.S. Army Corps of Engineers Mississippi Valley Division MRG&P and the National Great Rivers Research and Education Center (NGRREC). (2013-present)

Endangered pallid sturgeon (*Scaphirhynchus albus*) and threatened shovelnose sturgeon (*Scaphirhynchus platorynchus*) research on diet, life history, and conservation. U.S. Army Corps of Engineers—Mississippi Valley Division and New Orleans District. (January 2010-August 2013)

Invasive Asian carp (grass carp, silver carp, and bighead carp) studies on swimming behavior and control of young-of-year. Aquatic Nuisance Species Research Program (ANSRP). (September 2009-February 2010)

Other Research:

Plecoptera of North America (August 2012-present)

Scorpionflies and Hangingflies (Mecoptera) of Mississippi (May 2013-2015)

Caddisflies (Trichoptera) of Singapore, descriptions of new species (2012)

Morphological study and description of new stonefly, *Leuctra colemanorum* Harrison and Stark, (Plecoptera: Leuctridae) (2008-2010)

Morphological study and description of new stonefly, *Rhopalopsole alobata* Harrison and Stark, (Plecoptera: Leuctridae) (2007-2008)

Affiliations and Organizations:

International Society of Plecopterologists
International Society for River Science
Mississippi Roadside Vegetation Action Group
Sigma Xi
Society for Freshwater Science
American Entomological Society
Entomological Society of America
Mississippi Chapter of the American Fisheries Society
Clinton Community Nature Center, Clinton, MS
The Nature Conservancy

Outreach:

Occasional Columnist, Meet your neighbor series, *Vicksburg Post*, Vicksburg, MS

Entomology and Plant Camp, Aquatic Entomology Instructor, Mississippi State University, Starkville, MS

Kipp Delta Public Schools, Aquatic Ecology Programs, Helena, AR

The Mighty Quapaws Afterschool Program, Aquatic Ecology Programs, Clarksdale, MS

Lafayette County Schools, Entomology Program, Oxford, MS

Science Makers, Mississippi Museum of Natural Science, Jackson, MS